AN AIR MISSION PLANNING ALGORITHM FOR A THEATER LEVEL COMBAT MODEL

THESIS

Brian J. Griggs, Major, USAF

AFIT/GST/ENS/94M-5

Approved for public release; distribution unlimited

AFIT/GST/ENS/94M-5

AN AIR MISSION PLANNING ALGORITHM FOR A THEATER LEVEL COMBAT MODEL

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science Operations Research

Brian J. Griggs, B S.

Major, USAF

March 1994

Approved for public release; distribution unlimited

THESIS APPROVAL

STUDENT: Major Brian J. Griggs CLASS: GST-94M

THESIS TITLE: An Air Mission Planning Algorithm for a Theater Level Combat Model

DEFENSE DATE: 24 February 1994

COMMITTEE	NAME/TITLE/DEPARTMENT	SIGNATURE
Advisor	Gregory S. Parnell, Colonel, USAF Head, Department of Operational Sciences	
Reader	Lee J. Lehmkuhl, Major, USAF Department of Operational Sciences	Lee J. Lehmkuhl
Reader	Sam H. Parry, Professor Department of Operations Research Naval Post-Graduate School	

ACKNOWLEDGEMENTS

I could not have completed this thesis without the patience and help from my wife, Ruth. Likewise, my daughter Jenny provided many needed distractions which helped me keep my sense of humor! I also greatly appreciate the encouragement and guidance from my advisor, Col Greg Parnell, and my readers, Maj Lee Lehmkuhl and Professor Sam Parry. Finally, many thanks go to all of the other military and civilian analysts who helped along the way.

Brian J. Griggs

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

AFIT/GST/ENS/94M-5

ABSTRACT

This thesis describes the development of an air mission planning algorithm for the Joint Staff's Future Theater Level Model (FTLM). The overall problem scope was to develop an algorithm to handle major factors bearing on the combat mission planning problem while providing hook-ups for the FTLM architecture. Other aspects of the problem included finding the appropriate level of detail, developing a fast solving technique, and attempting to use existing data. The problem was handled by using some ideas from existing aircraft allocation algorithms and by adding some new techniques.

The proposed air mission planning algorithm supplies the optimum degree of force for campaign objectives by using a linear program (LP) to allocate the optimum number and type of aircraft and munitions against each target. The LP takes advantage of the force multiplying effects of mass and mutual support through its use of strike packages with SEAD and air-to-air escort. Additionally, a decision tree algorithm determines the best plan in light of the uncertainties of weather and weather forecasts.

This air mission planning algorithm omits many of the details in the actual aircraft tasking process, but provides fast, nearly optimal solutions which should approximate real world tasking results.

AN AIR MISSION PLANNING ALGORITHM FOR A
THEATER LEVEL COMBAT MODEL

I. INTRODUCTION

1.1 Purpose and Background

The purpose of this thesis is to develop an algorithm for generating air strike packages in the Future Theater Level Model (FTLM).

The Joint Staff at the Pentagon is developing the FTLM to analyze the results of force structuring decisions in a theater level campaign (21:1). FTLM is a computer simulation model which will handle uncertainty and variability in factors influencing operational decisions. The model will help examine what forces to deploy, how many, and when to deploy them. The FTLM architecture includes ground and air forces which operate on linked arc-node networks. Tactics for each side are based on intelligence perceptions of targets and enemy defenses. One area that is still undeveloped in this model is an algorithm for determining the composition of air strike packages (21:1).

An air strike package is a group of fighter and bomber aircraft that have been combined to provide mutual support against enemy threats while they achieve a common goal of destroying a set of targets. The basic principle of the strike package is to locally overwhelm an enemy's defenses through the use of surprise, mass, and mutual support. Tacticians achieve surprise by choosing a time and place to attack at

which the enemy is ill-prepared or unsuspecting. Mass means obtaining a large enough concentration of attackers to saturate enemy defenses. Mutual support is achieved by combining aircraft with complimentary capabilities so the package can protect itself and do the mission. For instance, F-15Cs have the ability to use radar missiles to shoot down opposing aircraft. EF-111s can disrupt enemy surface defense radars on a large scale, and F-111Fs can drop laser guided bombs with pinpoint accuracy. A package consisting of only one of these types of aircraft might be ineffective, but when all three types are combined properly in a strike package, they can protect each other and destroy the target.

Strike packages are normally constructed in several phases. First, the mission planner must select the right type and number of aircraft and munitions to efficiently destroy each target. Much data exists which can aid the planner in this selection process. For coordination purposes all of the aircraft chosen to attack a particular target form a flight or flights. Next, all flights attacking targets in the same vicinity are grouped into packages if aircraft speed restrictions and tactics are compatible. Last, the mission planner must add suppression of enemy air defense (SEAD) aircraft and air-to-air fighter escort or sweep aircraft to protect the groups of attackers. The addition of SEAD and escort aircraft depends on their availability, the enroute threats, the mission, and the type of aircraft in the package. Some aircraft types, such as the F-117, require little additional support. Likewise, for other missions, SEAD or escort might be ineffective against the particular threats, so they should not be used. In any event, each group of flights attacking targets in the same vicinity together with their SEAD and escort aircraft comprise a typical air strike package.

1.2 Scope of Research

1.2.1 Research Topics. Research subjects included decision analysis techniques, computer combat models, and AF doctrine concerning mission planning. Research began with an examination of current decision analysis techniques used in making decisions which involve uncertainties. The first problem during strike package construction is making aircraft allocation decisions when faced with uncertainties. These uncertainties include factors such as weather, target data, and the capabilities of enemy defenses. Incorrect assumptions about any of these factors could lead to disastrous results. Decision analysis provided tools to deal with these factors.

Examples of aircraft allocation algorithms in other models also proved helpful. The algorithms in these models provided useful concepts for dealing with large numbers of variables, for optimizing weapon loadouts, and for capturing some of the uncertainties mentioned above. In addition, the models gave a representative sample of the required level of detail for air campaign planning analysis.

Finally, some research was devoted to current unclassified rules accepted by Air Force planners. Although combat models need not adhere to doctrine, Air Force decision makers might not accept a model which produced results contrary to doctrine.

1.2.2 Problem Definition. After the initial research, accurate problem definition required several more steps. The first step was to capture all major factors influencing the air strike package development problem. Major factors include the enemy's intent, the number and types of his defenses, and the weather. These uncertainties must be handled effectively to hedge against unwanted outcomes and capitalize on desirable outcomes. The influence diagram developed in Section 2.1.1 helped shed light on the

interaction of factors influencing the problem.

Another part of problem definition was determining if an existing computer air planning model was suitable for use in the FTLM. By comparing the capabilities of existing computer models against the influence diagram, it became clear which models had the best algorithms. It also became clear that further development was needed on existing algorithms for FTLM use.

From this initial work in problem definition, the overall scope of the air strike packaging problem for the FTLM could be stated as follows: take ideas from existing aircraft allocation techniques, add modifications to address all factors captured by the influence diagram, and provide hook-ups for use in the FTLM architecture. Other parts of the problem included finding an appropriate level of detail, developing a reasonably fast solving technique, and attempting to use existing data.

1.3 Overview

The following chapters contain the research, a proposed algorithm, results, and recommendations. Chapter 2 contains findings from current literature on decision analysis, information on computer combat models, and a review of Air Force doctrine pertaining to air strike packages. Chapter 3 focuses on building the strike package algorithm for the FTLM. This chapter is divided into two phases. The first phase explains the development of strike packages for a given weather state. The second phase demonstrates how to choose the plan best suited for the weather forecast. Chapter 4 contains results and analysis from application of the algorithm to a small scale case, and Chapter 5 gives recommendations.

II. DISCUSSION OF LITERATURE

2.1 Decision Analysis Techniques

Influence diagrams and decision trees are effective tools for making decisions under uncertainty. They helped define the interrelationship of factors bearing on the air mission planning problem.

2.1.1 Influence Diagrams. An influence diagram is a decision analysis tool used to depict and solve a decision problem.[1] Figure 2-1 is an influence diagram representing the problem of allocating aircraft to targets during combat. This influence diagram depicts the theater commander's perspective of the problem. The time frame is for one tasking period, approximately six hours. (If the time frame was longer, then aircraft and munitions availability would show up as decision nodes instead of deterministic nodes.) The three basic decision nodes in this depiction include determination of a prioritized target list, air strike package development, and attack route selection. Iterations between these decisions may occur, but this is not shown. The influence of the Joint Force Air and Land Component Commanders (JFACC, JFLCC) is represented by deterministic nodes which affect target selection. The diagram shows how the uncertainties in the tactical situation relate to the

[1]The influence diagram is designed to capture the major factors which bear on a problem without so much detail that it confuses the issue. Robert Clemen, in *Making Hard Decisions*, describes how influence diagrams are constructed for decisions involving upcertainties. Clemen uses ellipses for chance events, rectangles for decisions, and double bordered shapes for decision outcomes or deterministic nodes. Arrows represent relevance of events to one another (4:34).

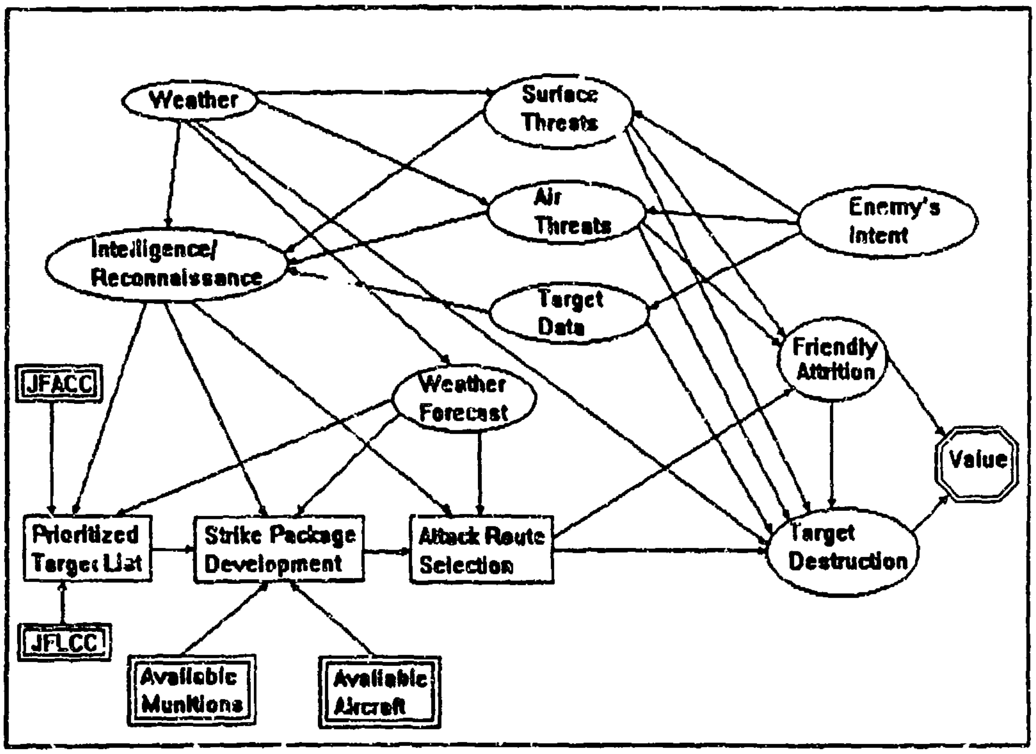

Figure 2-1. Influence Diagram for Air Strike Package Development

targeting, packaging, and routing decisions. Uncertainties, such as the weather and the enemy's def .. capability, are represented by elliptical chance nodes. Locations of targets and threats are shown as uncertainties which reflect the enemy's intent. Chance nodes are also used to represent the weather forecast and the intelligence/ reconnaissance update since these planning tools also have uncertainties. Five of the given chance nodes and the aircraft allocation decisions directly affect the amount of target destruction. The outcome or value node in the influence diagram is designed to capture the results of various decisions in light of the amount of target destruction and friendly attrition. This diagram is designed to concisely display the factors which are relevant to the aircraft allocation problem. Decision makers can quickly identify

relationships among the factors in the problem and can also readily determine if any pertinent factors have been omitted.

2.1.2 Decision Trees. Another decision analysis tool that Clemen identifies is the decision tree. Clemen says that decision trees show more detail than influence diagrams and that they also show chronology, from left to right (4:49). Uncertain events and decisions are represented by circles and squares respectively, similar to influence diagrams. Results are to the right of each branch.

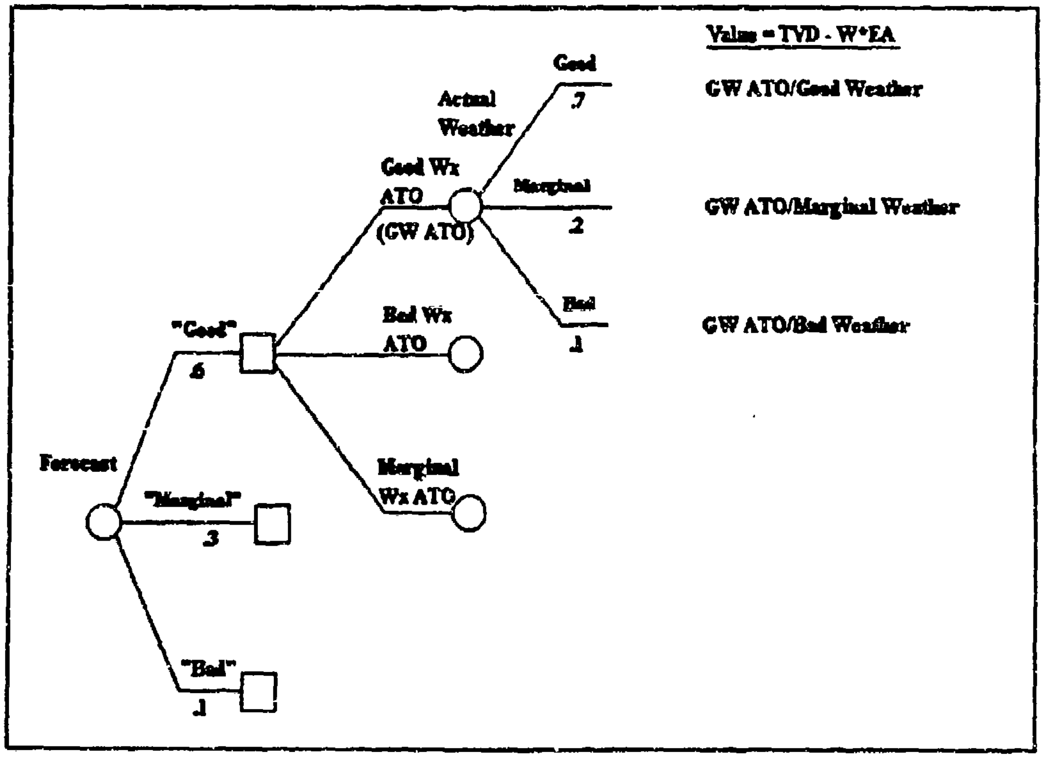

Figure 2-2. Decision Tree for Weather

Figure 2-2 depicts only part of the previous decision problem in a decision tree. The fact that all of the problem could not be concisely represented demonstrates a fault with decision trees: they get very cumbersome for complex decisions. This

decision tree shows an air tasking order (ATO) selection process based on the weather forecast, expected target value destroyed (TVD), and expected attrition (EA). The ATO with the maximum expected value for the forecast would be chosen.

Both the decision tree and influence diagram are powerful analytical tools. The decision tree shows sequence and much detail, but could get cumbersome. The influence diagram omits some detail, but focuses the viewer on the major aspects of the problem. These tools were useful in developing the air mission planning algorithm for the FTLM.

2.2 Combat Models

Several combat models offer excellent examples of aircraft allocation algorithms. The models do not all use strike packages as previously defined, but their algorithms provided important concepts for use in the FTLM. Models examined include the Theater Attack Model, TAC Thunder, the Conventional Targeting Effectiveness Model, the Theater Level Combat Model, the Optimal Marginal Evaluator, TACWAR, and the RAND Strategy Assessment System.

2.2.1 Theater Attack Model (TAM). In his thesis, Jackson describes TAM as "a large scale linear program (LP) used to aid senior decision makers in making tough budget procurement decisions for the United States Air Force" (12:X). TAM can also determine munitions requirements, costs of various force structures, and expected attrition (12:A-3).

TAM is formulated as a linear program (LP). The objective function of this model maximizes the total target value destroyed by the aircraft and munitions in its scenario. The user can input campaign objectives through constraints. The model

uses decision variables which represent each sortie. Each sortie is defined by a particular aircraft and ordnance combination to maximize target value destroyed for a given target, weather, time period, and distance to the target (12:A-1).

For use in the FTLM, TAM's aircraft allocation algorithm has several advantages and disadvantages. One advantage is that the LP is a fairly simple algorithm for which many solvers exist. Another advantage of the model is that it addresses many of the major factors that will impact the mission: weather, distance, aircraft type, munitions, and attrition. In addition, the ability to add campaign objectives through constraints and target values provides much flexibility. A disadvantage is that the decision variables are very detailed. The problem with this level of detail is that to capture all possible decision variables as they are defined above, the model must handle 8.75 million variables (12:A-1). Solving a problem with this many variables requires a powerful and expensive computer and software set up. Another problem with the formulation is that the aircraft sorties are not grouped into strike packages (12:3-9). As a result, the advantages of mutual support and mass are not represented in the model.

2.2.2 TAC Thunder. TAC Thunder is a combat model which simulates air war, ground war, and resupply (1:2-1). According to the TAC Thunder manual, "The air war models the mission planning sequence of explicit air missions and the execution of those missions" (1:2-1). Target lists are developed from simulated intelligence sources, and aircraft are allocated to missions based on an overall set of objectives. These objectives are input by the user. The form of this input is in percentages of total aircraft which will perform given missions. The manual calls these percentages

the "mission allocation" (1:11-1). For example, at the beginning of the simulated war, the user would want to gain air superiority. To meet this objective, he would allocate large percentages of aircraft to perform air-to-air and SEAD missions. Within each mission allocation category, the model automatically prioritizes targets (except certain strategic targets) based on factors such as distance from the FLOT, weights for target subcategories, and amount of previous target destruction (1:11-5). Thunder then uses heuristics to determine the number of aircraft to send to each target (1:11-11).

TAC Thunder's LP and heuristics are designed to optimize sortie allocation in terms of mission effectiveness against a target list (1:11-3). This target list is derived from intelligence and reconnaissance reports that occur throughout the campaign (1:11-26). Constraints in the LP include sortie availability, munitions availability, and the mission allocation. The manual summarizes the aircraft allocation algorithm as follows:

> The model tries to assign the available sorties to missions in percentages exactly matching the mission allocation. Since the effectiveness is different for each type of aircraft, the allocation is treated as a transportation problem. The mission allocation is the goal, the available sorties are the resources, and the cost of assigning sorties to a mission is set to one hundred minus the mission effectiveness. The Network-Simplex method is used to solve the problem. (1:11-4)

After deciding on aircraft and munitions combinations for the various targets, TAC Thunder looks at perceived enemy air defense threats along the routes. Based on these perceived threats, it then assigns SEAD to flight groups as required (1:11-31). Based on routing distance in enemy territory, Thunder also assigns air-to-air fighter escort (1:11-32).

The TAC Thunder model has features which were useful in the FTLM aircraft

packaging algorithm. Thunder's allocation techniques for SEAD and escort provided insight for SEAD and escort allocation in the FTLM.

One of TAC Thunder's weaknesses appears to be the user defined mission allocation. Using this mission allocation, the model then attempts to meet the defined mission percentages with its aircraft allocation algorithm. It seems like a more logical method would employ user defined target priorities or objectives and have the algorithm determine the optimal number of aircraft for each mission category.

2.2.3 Conventional Targeting Effectiveness Model (CTEM). CTEM is an optimization model designed to answer force structuring questions for air campaign planners (5). Like TAM, the model does not involve stochastic simulations, and it does not have a ground force scenario. Also, both models use the same data base, Saber Selector. Unlike TAM, CTEM uses a goal programming LP to meet user input campaign objectives (5). The goal programming ensures that targets are hit in an order appropriate to satisfy the user's objectives (6). The LP allocates the optimal aircraft and weapon load out to each target, while providing a fractional amount of SEAD support based on the threat. Air strike packages can then be created by post-processing. No air-to-air fighter escort is used (5).

CTEM has many of the same strengths and weaknesses as TAM, but CTEM was designed for air campaign planners, whereas TAM was designed for budget planners. As a result, CTEM has a few advantages over TAM when considered for use in the FTLM. For one, CTEM creates strike packages which incorporate SEAD. In addition, CTEM has no budget factors which might cloud the issue.

CTEM also has a few weaknesses. The first is the fractional use of SEAD

aircraft. This is most likely the result of attempting to avoid integer vaiables and may be an unavoidable problem. The second problem is the lack of fighter escort aircraft for strike packages. MCM 3-3, *Fighter Fundamentals,* says fighter escort is normally a required part of the package (8:3-46).

2.2.4 Other Models. Several other models were examined for possible use in the FTLM. These models included RAND's Theater Level Combat Model (TLC), the Optimal Marginal Evaluator (OME III/IV), TACWAR, and the RAND Strategy Assessment System (RSAS).

RAND is developing TLC to analyze the results of force structuring and weapon system procurement decisions in a joint theater level campaign (18). The model uses a deterministic air planning approach involving game theory, while mission execution is represented with a high resolution simulation on an arc-node network (17). While this model appears very promising, its aircraft allocation algorithm was not considered for use in the FTLM because TLC is still under development.

OME IV also looked like a promising model, but it is still under development by STR Corporation. OME III in now in use. Like TLC, OME uses game theory for air planning; however, OME III handles only three aggregated aircraft types per side (10). OME IV will handle most existing aircraft types when complete (13). Again, since OME IV is still under development by STR, it was not considered further.

Next, TACWAR was examined. TACWAR is used for "analyzing comparative significance of alternative force sizes, mixes, or courses of action" (2:11-2). It does not "represent the outcome for a particular situation" or conflict (2:11-2). The TACWAR user accomplishes most of the aircraft allocation and campaign planning

through his own inputs to the model. TACWAR then uses heuristics and a deterministic approach to calculate results. TACWAR was not considered for use in the FTLM because it primarily relied on the user's air planning.

Last, RSAS was reviewed. RSAS is designed "to support balance assessment, contingency analysis, and military training" (3:xiii). Like TACWAR, it is not designed to predict conflict outcomes, and much of the air planning is accomplished manually through user input (3:182) Therefore, RSAS was not considered further.

2.2.5 Model Summary. TAM, TAC Thunder, and CTEM offer the best concepts for use in the air strike package algorithm for the FTLM. Table 2-1 shows a summary of these three models. TAM provides a fairly simple (although large) LP formulation which addresses most of the major planning factors, such as weather, target data, and expected attrition. It also provides the flexibility for adding campaign objectives through target values and constraints. TAC Thunder offers logical aircraft packaging ideas, some useful target prioritization concepts, and an extensive data base. CTEM also creates strike packages and provides many of TAM's strengths.

2.3 Air Force Doctrine

Warden provides an important concept for consideration during this research. He says "A successful campaign clearly was contingent on a good plan, and construction of a good plan required a good understanding of the forthcoming action" (20:141). Therefore, no matter how good the aircraft packaging algorithm for the FTLM is, the user must still provide the model with a reasonable overall plan through the objectives that he inputs. The algorithm cannot even win a simulated war without a well thought out plan of action.

Table 2-1. A Comparison of Aircraft Allocation Techniques

	TAM	TAC THUNDER	CTEM
Objective Function	An LP maximizes TVD while allocating the optimum aircraft and munition against each target.	A transportation LP meets user input mission percentages with the most effective aircraft for each mission.	A goal-programming LP meets the user's campaign goals while allocating the optimum aircraft and munition against each target.
Campaign Objectives	Input through target values and constraints.	Input through mission percentages and target priorities.	Input through prioritized targeting goals.
Target Prioritization	Based on target values.	Input manually or prioritized automatically by heuristics.	Targets are prioritized based on the campaign goal they support. Campaign goals are fulfilled sequentially.
Aircraft Packaging	No strike packages used.	Creates strike packages.	Creates strike packages through post-processing.
SEAD and Air-to-Air Escort Use	No SEAD or escort used.	SEAD priorities are based on aircraft vulnerability. Escort priorities are based on distance flown in enemy territory.	The LP assigns fractional SEAD aircraft as required. No escort aircraft are used.
Planning Horizon	User input, but normally the entire campaign	User input, but normally 12 hours to take advantage of changing intelligence and reconnaissance information.	User input, but normally the entire campaign.
Weather Planning	Aircraft and munitions allocation is based on the expected percent of each weather state.	PKs are the weighted average of the PKs for each weather state.	PKs are the weighted average of the PKs for each weather state.

Unclassified sources on campaign planning offer fairly general discussions about strike package construction. AFM 1-1, *Basic Aerospace Doctrine*, gives an overview of the subject. MCM 3-3, *Mission Employment Tactics, Fighter Fundamentals, F-111*, provides more specific information. Last, an article from the *Airpower Journal*, called "Air Campaign Planning" offers additional guidance.

2.3.1 Basic Doctrine. AFM 1-1 discusses basic rules of doctrine which govern tactics in air warfare. Several statements in this manual apply in a general manner to strike package construction:

1. "There is no universal formula for the proper employment of aerospace power in a campaign"(7:125).

2. "The nature of the enemy should be a primary consideration in campaign decisions"(7:125).

3. "Planners should examine the full range of available air and space assets when selecting the systems required to achieve the objective of the campaign"(7:125).

In other words, this manual confirms that campaign planning is an art governed by few rules, and it implies that in constructing strike packages, the nature of the enemy's defenses and the target must be major considerations.

2.3.2 Fighter Fundamentals. MCM 3-3 offers some important tactical concepts that bear on the problem. Strike packages are used to "take advantage of threat weaknesses, concentrated firepower, and dedicated EC (electronic combat) assets" (8:3-45). To take advantage of threat weaknesses, planners should route the package through the weakest defenses. To benefit from dedicated EC, increasing package size allows more aircraft to receive jamming protection from the limited numbers of EC aircraft. Concerning size constraints, MCM 3-3 says that the package could contain up to ninety aircraft plus SEAD support, but coordination time and effort is the limiting factor (8:3-45,47). One final consideration in package development is stated in this manual: "A large force employment package has to be protected by a dedicated CAP [combat air patrol] with the ultimate goal of having a large number of aircraft penetrate a hole in the forward area in a short period of time" (8:3-46). All of these

considerations apply to the strike package algorithm.

2.3.3 Campaign Planning. McCrabb provides a view of how mission planners should distill air campaign objectives into sortie allocations. He begins by explaining that air objectives should focus on hitting the enemy's centers of power, such as leadership, key production, population, or forces in the field (14:20). He further states that these objectives must be clear and concise, attainable, and measurable so that planners can readily grasp them (14:19). Based on these objectives, he provides the following procedure for putting the campaign together (14:21):

1. Identify targets and assign priorities. Specify desired damage.
2. Identify the appropriate weapon system for each target.
3. Allocate and apportion aircraft.

The second two steps should apply directly to the strike package algorithm. It must identify the appropriate aircraft for a given prioritized target list. Then it must allocate and apportion aircraft into strike packages. Concerning this last step McCrabb says:

> Let me emphasize that this is a bottom-up approach. You don't just pull figures from thin air (e.g., 30 percent for counterair, 30 percent for strategic attack, 20 percent for interdiction, and the rest for close air support). You first decide what has to be done and in what priority, and then you determine how those sortie figures translate into percentages (or priorities) by mission. (14:21)

McCrabb's "bottom-up approach" appears to conflict with the methodology of TAC Thunder, TACWAR, and RSAS, but not TAM, CTEM, TLC and OME. The FTLM algorithm in this thesis incorporates McCrabb's approach.

2.4 Summary of Literature

Both influence diagrams and decision trees offer excellent capabilities for solving the strike package construction problem. These tools were used along with basic rules of air doctrine from AFM 1-1 and MCM 3-3 to build an algorithm for the FTLM. The Theater Attack Model illustrates how many variables influence the sortie allocation problem. It also demonstrates how optimizing with all of these variables can create an enormous problem. On the other hand, TAC Thunder and CTEM offer excellent examples of strike packaging concepts using air-to-air escort and SEAD. Finally, McCrabb offers an air campaign planning procedure which conflicts with some models but supports others. Nevertheless, the algorithm for FTLM was based on McCrabb's approach. All of these references were useful in building the FTLM's air strike package algorithm.

III. BUILDING THE STRIKE PACKAGE ALGORITHM

3.1 Approach

The top down design approach was used as much as possible. Top down design requires the analyst to model only the most important factors, to use the lowest level of resolution feasible, to keep it as simple as possible, and to state assumptions clearly (15:4).

In addition, concepts from TAM and TAC Thunder were incorporated into the algorithm. Parts of TAM's LP structure and ideas from Thunder's SEAD and escort allocation techniques were used.

3.1.1 Assumptions. Here are the assumptions the algorithm uses in the mission planning process:

1. A day in the campaign is divided into four periods. During each period, all available assets are tasked at once. It is assumed that the scheduling of TOTs, staggered takeoffs, refuelling times, and alert aircraft is done later in the planning phase, not during the strike package building phase.

2. In the prioritization phase, targets are prioritized by target type (bridge, hardened aircraft shelter, column of vehicles, etc) and location. This procedure eases the target prioritization process and reduces the number of variables in the aircraft allocation problem.

3. The target prioritization phase resolves perceptions of target data and operating capacity into target values.

4. The probability of damage to a target increases exponentially as a function of the number of attacking aircraft.

5. Perceptions of surface threats determine the probability of survival for each aircraft enroute to each target location.

6. The probability of survival of each aircraft of a single type remains the same in all flights assigned to the same location unless the flight receives escort or SEAD support.

7. SEAD improves aircraft survivability against ground threats only. SEAD can also help somewhat against air threats by targeting ground control intercept (GCI) and early warning (EW) radars, but this benefit is assumed negligible.

8. The probability of survival against interceptors decreases with distance flown in enemy territory.

9. Weather phenomena are assumed to be uniform across the entire target array.

10. The change in the probability of target kill and vulnerability to surface threats is negligible throughout different weather states for the same aircraft flying the same route to the same target with the same ordnance.

3.1.2 Methodology Overview. The strike package planning process incorporates the above assumptions. Planning involves two phases. In the first phase, a mixed integer program (MIP) assigns flights of aircraft to targets and picks the best munition for each flight. As the program selects aircraft for targets, it optimizes the use of limited air-to-air escort fighters and SEAD aircraft to support the strike packages. An alternative continuous variable LP will also be discussed in Phase I. In the second phase, a decision tree algorithm chooses the best weather plan for a given forecast.

3.2 Phase I: Building Air Strike Packages

3.2.1 The Concept. To plan effective strike packages and weapon load-outs, a MIP or optional LP maximizes expected target value destroyed (TVD) while being penalized for expected attrition. The algorithm uses target values in order to expend most effort destroying the targets with the most weight. Decision variables reflect the number and type of aircraft and munitions needed for each target. They also indicate whether or not flights assigned to a given target and location will receive SEAD or escort support. The program allocates aircraft for one six hour tasking period and a given weather state.

3.2.2 Mixed Integer Programming Option. Given data on the survival and target killing capabilities of each aircraft, the MIP option maximizes TVD minus the attrition penalty. The MIP uses continuous decision variables for aircraft flights and binary (zero or one) decision variables for SEAD and air-to-air escort allocation to the flights.

The calculation of expected TVD for each aircraft type, requires the aircraft's probability of survival against the air threat (PSA) and probability of survival against the ground threat (PSG). These probabilities are based on numerous factors including radar cross section, on-board electronic countermeasures, aircraft speed, maneuverability, air-to-air radar effectiveness, self defense weapons, radar homing and warning receivers, and crew training. (For demonstration purposes, Chapter 4 employs notional values for these probabilities and for changes in these probabilities caused by SEAD and escort support.) The probability of destroying a target is a function of PSA, PSG, and the probability of an individual aircraft destroying a target (PKI) given that it has survived to the weapon delivery. The formula for computing the total

probability of target destruction (PKT) for N aircraft is $PKT = 1-\{1-(PSA)(PSG)(PKI)\}^N$. This formula was adapted from a formula in *Introduction to Operations Research* by Ye. S. Venttsel (19:191). Use of this formula requires several assumptions. The first is that individual aircraft are hit by ground or air threats independently of each other. The second is that PKI increases exponentially as a function of the number of attacking aircraft. The third is that all N aircraft are of the same type, using the same delivery and munition against the same target (19:191). The expected target value destroyed for each formation of aircraft is the product of PKT (as computed above) and target value (TVAL). TVAL is received from the target prioritization phase. Decision variables represent the number of formations of a single type of aircraft against a single target type with the same munition for the given weather.

In addition to maximizing TVD, the objective function is simultaneously penalized for expected attrition. The expected value of attrition (EA) for N aircraft is: $EA = N\{1 - (PSA)(PSG)\}$. The addition of SEAD support increases PSG, and the addition of air-to-air escort increases PSA. The penalty value for a single aircraft lost is represented by W. Combining expected TVD and the attrition penalty, the MIP is presented below.

<u>Definitions:</u>

$x_{amptrces}$: The decision variable x represents the number of flights of aircraft type a assigned munition m to acheive PK p against target type t at sector rc, with or without air-to-air escort e or SEAD s.

a: aircraft type (F-15, F-16, etc)

m: munitions type (laser guided, general purpose, cluster, etc.)

p: desired PK of flight (.6, .8)

t: target type (column of vehicles, hardened shelter, runway, etc.)

r: target distance in enemy territory (row 1, 2, or 3)

c: target column location in enemy territory (columns 0-9)

e: air-to-air escort (with, without)

s: SEAD (with,without)

N_{ampt}: number of aircraft using munition m required to achieve desired PK p

$PKT_{amptrces}$: total PK for a flight of aircraft against a target. This value represents the fractional kill for an area target or probability of damage for a point target.

PKI_{amt}: PK of an individual aircraft given that the aircraft has survived to the weapon delivery

$TVAL_{trc}$: target value assigned to target type t at sector rc

W: user defined attrition penalty

$EA_{amptrces}$: expected attrition for a flight of aircraft

PSA_{are}: probability of survival against air threats for aircraft a when assigned to row r with or without escort e

PSG_{arcs}: probability of survival against ground threats for aircraft a when assigned to sector rc with or without SEAD s

Objective function (to be maximized):

$$Value = \sum_a \sum_m \sum_p \sum_t \sum_r \sum_c \sum_e \sum_s x_{amptrces}[(PKT_{amptrces})(TVAL_{trc}) - (EA_{amptrces})(W)] \tag{3-1}$$

where

$$EA_{amptrces} = (N_{ampt})[1-(PSA_{arc})(PSG_{arcs})] \tag{3-2}$$

$$PKT_{amptrces} = 1-[1-(PSA_{arc})(PSG_{arcs})(PKI_{amt})]^{N_{ampt}} \tag{3-3}$$

<u>Constraints:</u>

The constraints include aircraft and munitions availability as well as aircraft range restrictions. The constraints are as follows:

Available aircraft by type:

$$\sum_{m}\sum_{p}\sum_{t}\sum_{r}\sum_{c}\sum_{e}\sum_{s} x_{amptrces}(N_{ampt}) \leq NUMAC_{a} \tag{3-4}$$

$NUMAC_a$: number of aircraft type a available in period

Escort package assignments:

$$\sum_{a}\sum_{m}\sum_{p}\sum_{t}\sum_{s} x_{amptrc1s} \leq (NTGT_{rc})(EP_{rc}) \tag{3-5}$$

$NTGT_{rc}$: number of targets in each sector rc

EP_{rc}: This decision va iable will equal one for a sector if an air-to-air escort package is assigned to flights with targets at that location; otherwise it will equal zero.

Available air-to-air escort packages:

$$\sum_{r}\sum_{c} EP_{rc} = NUMEP \tag{3-6}$$

$NUMEP$: total number of escort packages available in period

SEAD package assignments:

$$\sum_{a}\sum_{m}\sum_{p}\sum_{t}\sum_{e} x_{amptrce1} \leq (NTGT_{rc})(SP_{rc}) \qquad (3\text{-}7)$$

SP_{rc}: This decision variable will equal one for a sector if a SEAD package is assigned to flights with targets at that location; otherwise it will equal zero.

Available SEAD packages:

$$\sum_{r}\sum_{c} SP_{rc} = NUMSP \qquad (3\text{-}8)$$

$NUMSP$: total number of SEAD packages available in period

Hit each target only once per period:

$$\sum_{a}\sum_{m}\sum_{p}\sum_{e}\sum_{s} x_{amptrces} \leq NTYPE_{trc} \qquad (3\text{-}9)$$

$NTYPE_{trc}$: number of targets of type t in each sector

Available munitions:

$$\sum_{a}\sum_{p}\sum_{t}\sum_{r}\sum_{c}\sum_{e}\sum_{s} x_{amptrces}(N_{ampt})(B_{amt}) \leq NMUNS_{m} \qquad (3\text{-}10)$$

$NMUNS_{m}$: number of munitions of type m available in period

B_{amt}: number of bombs per aircraft

Range restrictions:

$$\sum_{m}\sum_{p}\sum_{t}\sum_{c}\sum_{e}\sum_{s} x_{1mpt3ces} = 0 \qquad (3\text{-}11)$$

Aircraft type 1 cannot fly long range missions to row 3.

Non-negativity:

$$x_{amptrces} \geq 0 \qquad (3\text{-}12)$$

The product of the numbers for each summation index indicates the number of decision variables. In turn, the numbers for each index depend on the desired level of detail for the entire model. For instance, for each period assuming no more than 10 aircraft types were used, 20 munition types, 2 different PKs, 40 target types, and 30 sectors, the problem would have 1,920,000 decision variables. In addition, sixty of these variables would be binary. Increasing or decreasing any of these index levels would result in a change to the overall problem size and solution time. Since a MIP of this magnitude would probably take quite awhile to solve, a fast continous variable LP which uses heuristics for SEAD and escort allocation might prove more useful.

3.2.3 Linear Programming Option. A combination of linear programming and heuristics can efficiently solve the previously described MIP. First, if the sixty integer SEAD and escort assignment constraints are relaxed to allow continous solutions between zero and one, the program will no longer contain any integer restrictions. It could then be solved as an LP; however, the solution would contain fractional SEAD and escort packages which would overstate the number of strike packages that could be covered. To fix this problem, a simple algorithm could make a reasonable allocation of SEAD and escort packages to strike packages. The steps of the algorithm are as follows:

1. Run the MIP with its integer restrictions relaxed to continous.

2. Using the relaxed integer solution, assign the available SEAD packages to the sectors with the highest values for SP_{rc}. Assign the available air-to-air escort packages to the sectors with the highest values for EP_{rc}.

3. With the SEAD and escort package assignments fixed, the program is now a

continuous variable LP. The only decision variables are $x_{amptcws}$. This LP will now optimally allocate all aircraft around the SEAD and escort packages and provide the final solution.

As a final note, this LP might not provide the optimum overall solution because of the heristics, but it should be much faster than the previous MIP. Furthermore, the solution will be only slightly suboptimal because running the final LP with SEAD and escort fixed will optimally reallocate the aircraft to their targets.

3.3 Phase II: Handling the Weather Problem

To obtain the best plan for weather, the MIP or LP in Phase I is solved once with each of three different data bases: one solution provides a good weather ATO; one provides a bad weather ATO; and the third yields a marginal weather ATO. Each provides a different objective function value. Next, a set of heuristics determines the value ($Value = TVD - W^*LA$) for each ATO given the three different weather states. (See Table 3-1.) Finally, a decision tree is used to solve the problem of maximizing expected value for the given forecast using probability data. (See Figure 3-1.)

The desired level of detail for the FTLM will determine the number of weather states to use and their corresponding definitions. For instance, for the given decision tree "good weather" could be defined as at least 5 miles visibility and a 5000 foot ceiling, "marginal weather": at least 3 miles visibility and a 1000 foot ceiling, "bad weather": anything worse than marginal. For each defined weather state the appropriate munitions and delivery tactics would be put into the data base. Phase I could then solve for the optimal aircraft, munition, and value for each weather state. Last, the decision tree would then maximize expected value against the weather.

Table 3-1. Heuristics for Multiple Weather States.

Type ATO	Actual Weather	Results for given weather
Good weather	Good	Value stays the same
	Marginal	Value decreases by the TVD for munitions which cannot be dropped in marginal weather
	Bad	Value decreases by the TVD for munitions which cannot be dropped in marginal or bad weather
Marginal weather	Good & Marginal	Value stays the same
	Bad	Value decreases by the TVD for munitions which cannot be dropped in bad weather
Bad weather	Any type	Value stays the same

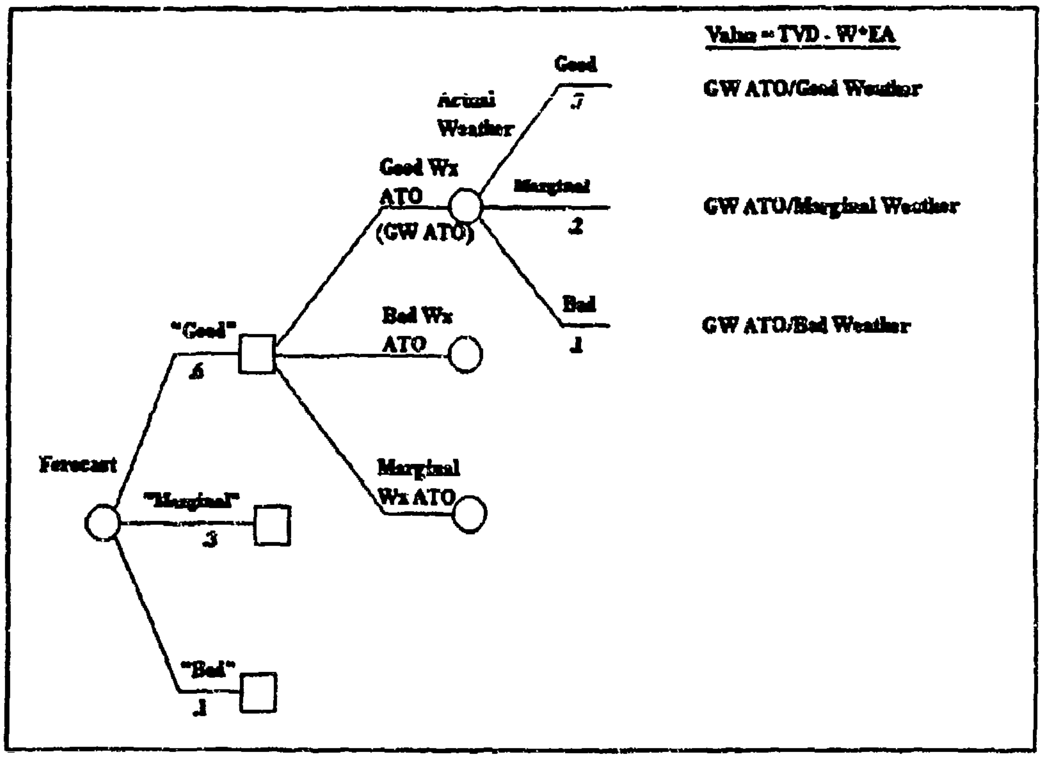

Figure 3-1. Weather Decision Tree

3.4 A Comparison of Aircraft Allocation Techniques

The proposed FTLM aircraft allocation method has many similarities to existing combat models. In particular, since the Phase I algorithm is similar to TAM, a comparison might be useful. Similarities include the decision variable indices and the use of target values in the objective functions. The differences stem from the fact that TAM was designed for budget and procurement planning, not for mission planning. As a result, TAM does not build strike packages or allocate dedicated SEAD and escort aircraft as Phase I does. Attrition affects TAM's objective function mainly by decreasing an aircraft's probability of hitting the target. In Phase I attrition decreases PK, but unlike TAM, expected attrition is treated as a penalty to be subtracted from TVD. Next, decision variables in Phase I do not reflect time period because the program must be re-solved four times a day for each day of the war to reflect changing target values and intelligence perceptions. TAM is solved once for the entire war. Also, decision variables in Phase I do not reflect weather bands. Instead, it relies on a data base for each weather state. Phase II selects the appropriate good, marginal, or bad weather ATO with the decision tree.

Phase I also uses some ideas from TAC Thunder for SEAD and escort allocation. Thunder prioritizes SEAD support based on aircraft vulnerability and enroute threats; Phase I does essentially the same thing. Thunder prioritizes escort based on distance flown in enemy territory. Phase I uses distance flown and aircraft vulnerability. Table 3-2 shows a comparison of FTLM's proposed strike package planner (including Phase I and II) and the aircraft allocation techniques from the models in Table 2-1.

Table 3-2. A Comparison of Aircraft Allocation Techniques

	TAM	TAC THUNDER	CTEM	FTLM
OBJECTIVE FUNCTION	An LP maximizes TVD while allocating the optimum aircraft and munition against each target.	A transportation LP meets user input mission percentages with the most effective aircraft for each mission.	A goal-programming LP meets the user's campaign goals while allocating the optimum aircraft and munition against each target.	Phase I maximizes TVD subject to an attrition penalty while allocating the optimum aircraft and munition against each target.
CAMPAIGN OBJECTIVES	Input through target values and constraints.	Input through mission percentages and target priorities.	Input through prioritized targeting goals.	Input through target values and constraints.
TARGET PRIORITIZATION	Based on target values.	Input manually or prioritized automatically by heuristics.	Targets are prioritized based on the campaign goal they support. Campaing goals are fulfilled sequentially.	Based on target values.
AIRCRAFT PACKAGING	No strike packages used.	Packages consist of aircraft flights assigned to targets in the same vicinity.	Creates strike packages through post-processing.	Packages are optimized for target destruction and defense against enroute threats.
SEAD AND AIR-TO-AIR ESCORT USE	No SEAD or escort used.	SEAD priorities are based on aircraft vulnerability. Escort priorities are based on distance flown in enemy territory.	The LP assigns fractional SEAD aircraft as required. No escort aircraft are used.	SEAD and escort aircraft are optimally allocated to strike packages.
PLANNING HORIZON	User input, but normally the entire campaign.	User input, but normally 12 hours to take advantage of changing intelligence and reconnaissance information.	User input, but normally the entire campaign.	Phase I plans only one tasking period (6 hrs) at a time. This way, changing perceptions of threats and new target values can be included.
WEATHER PLANNING	Aircraft and munitions allocation is based on the expected percent of each weather state.	PKs are the weighted average of the PKs for each weather state.	PKs are the weighted average of the PKs for each weather state.	Phase II chooses the best ATO based on the conditional probabilities of various weather states for a given forecast.

IV. RESULTS

4.1 Phase I: Building Strike Packages.

4.1.1 Small Scale Example. This section shows the model's strike package plan for a single period in a small scale air campaign. The example includes fifty F-15Es, fifty F-111Fs, fifty A-6s, twenty EF-111s, twenty EA-6Bs, twenty F-4Gs, and forty F-15Cs. For this demonstration, a SEAD package consists of four EF-111s or EA-6Bs and two F-4Gs. An air-to-air escort package consists of four F-15Cs. The example also includes 196 targets of 6 different types: hardened aircraft shelters, runways, hardened command centers, factories, bridges, and tanks. An unlimited supply of MK-82 General Purpose bombs, Durandal runway munitions, AGM-65 Maverick air-to-surface missiles, and GBU-10 Laser Guided Bombs is available. The weather is good.

All targets lay in a grid which represents the targets' relative depth and lateral position in enemy territory. (See Figure 4-1 for the grid and 4-2 for its legend.) The maximum depth of each row corresponds to the maximum combat radius of various fighters. For instance, the F-15Es and F-111Fs can penetrate to row three while A-6s can only make it to row two. (If F-16s were in the scenario, their limit would be row one.) Columns divide the rows into sectors. A sector is defined by its row and column numbers. Although the columns indicate relative lateral displacement, they do not necessarily need to be adjacent. In other words, when overlaid on a map, the grid will be spread out, and areas with few or no targets will be excluded from the grid.

Target values reflect the campaign objectives. Figure 4-1 shows the value

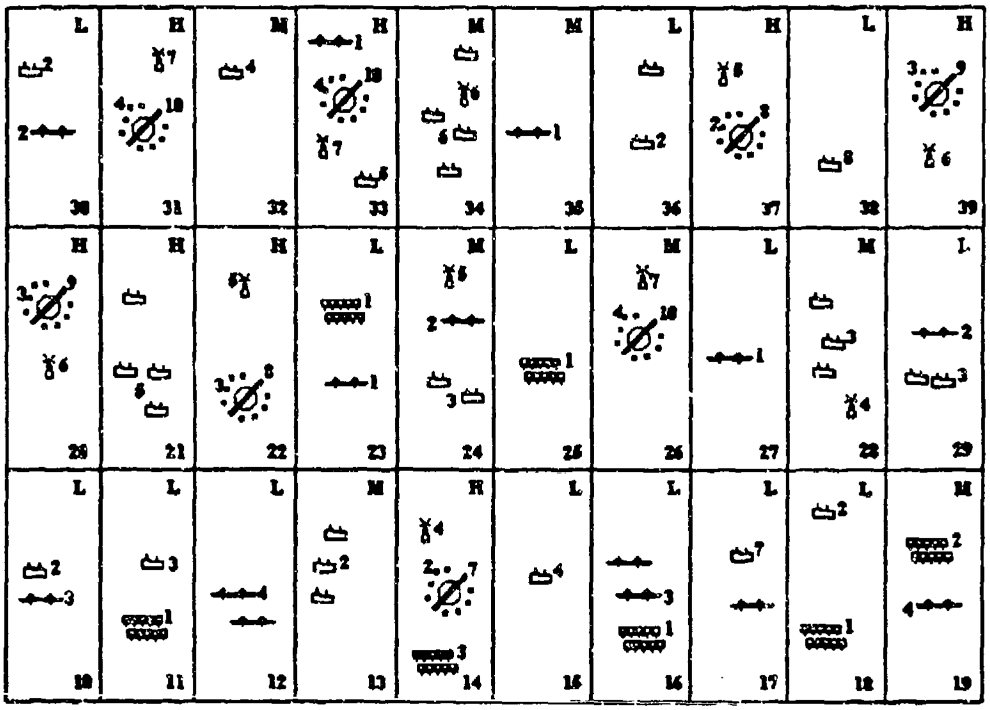

Figure 4-1. Targeting Grid

assigned to each target. For instance, since the objective in this case is to reduce the enemy's offensive air capability, runways have high values. Likewise, some of the command centers which direct the enemy's air campaign also have high values. Since the enemy ground forces are not advancing, most tanks have low values. On the other hand, the tanks in sector 14 have higher values since their destruction would help friendly forces capture the airfield.

Notional probabilities reflect each aircraft's probability of survival against the perceived surface and air threats. These probabilities are in Tables 4-1 and 4-2. Basically, the F-15E is the least vulnerable to air and surface threats, while the A-6 is the most vulnerable. Each sector on the grid has, in the upper right hand corner, the

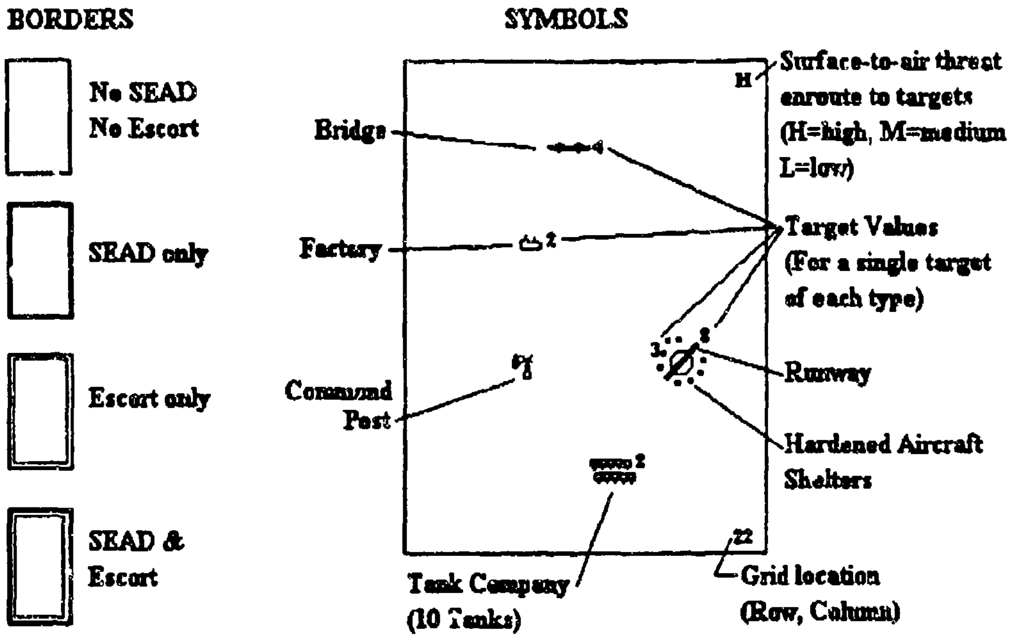

Figure 4-2. Grid Legend

perceived surface threat enroute to that sector (L, M, H). PSG decreases for each aircraft as the surface threat increases. In addition, support from a SEAD package decreases an aircraft's vulnerability to the surface-to-air threat by a notional amount of 50 percent. The perceived air interceptor threat increases with the depth of each sector in enemy territory. So, as depth increases, PSA decreases. Support from an air-to-air escort package decreases an aircraft's vulnerability to the interceptor threat by a notional amount of 50 percent.

Last, PKs for munitions are also notional, but are reasonable in a relative sense; for example, smart weapons have the highest PKs. These probabilities are in the GAMS program in Appendix A.

Table 4-1. Probability of Survival Against Air Threats (PSA)

		Row 1	Row 2	Row 3
F-15E	with escort	.9980	.9960	.9940
	without escort	.9960	.9920	.9880
F-111F	with escort	.9965	.9930	.9895
	without escort	.9930	.9860	.9790
A-6	with escort	.9955	.9910	
	without escort	.9910	.9820	

Table 4-2. Probability of Survival Against Ground Threats (PSG)

		High threat	Medium Threat	Low Threat
F-15 E	with SEAD	.995	.998	.999
	without SEAD	.990	.995	.998
F-111F	with SEAD	.992	.996	.998
	without SEAD	.985	.992	.996
A-6	with SEAD	.989	.994	.997
	without SEAD	.978	.989	.994

The MIP model for this scenario was implemented in the GAMS/ZOOM (11)(22) software package with a VMS operating system on a Digital Equipment Corporation minicomputer. This example produced 17,280 decision variables, including 60 binary variables. The solution time to optimality was about twenty-one minutes. The solution is shown in Figure 4-3. The GAMS program and a complete breakdown of this solution are in Appendix A.

The model produced reasonable air strike packages. Figure 4-3 shows that the model put most aircraft into packages which had SEAD and air-to-air escort support. Most likely, the model allocated SEAD and escort to the same packages to provide the most benefit to the greatest number of aircraft. (In a Desert Storm type scenario, the ratio of SEAD and escort packages to total attacking aircraft would be smaller, and

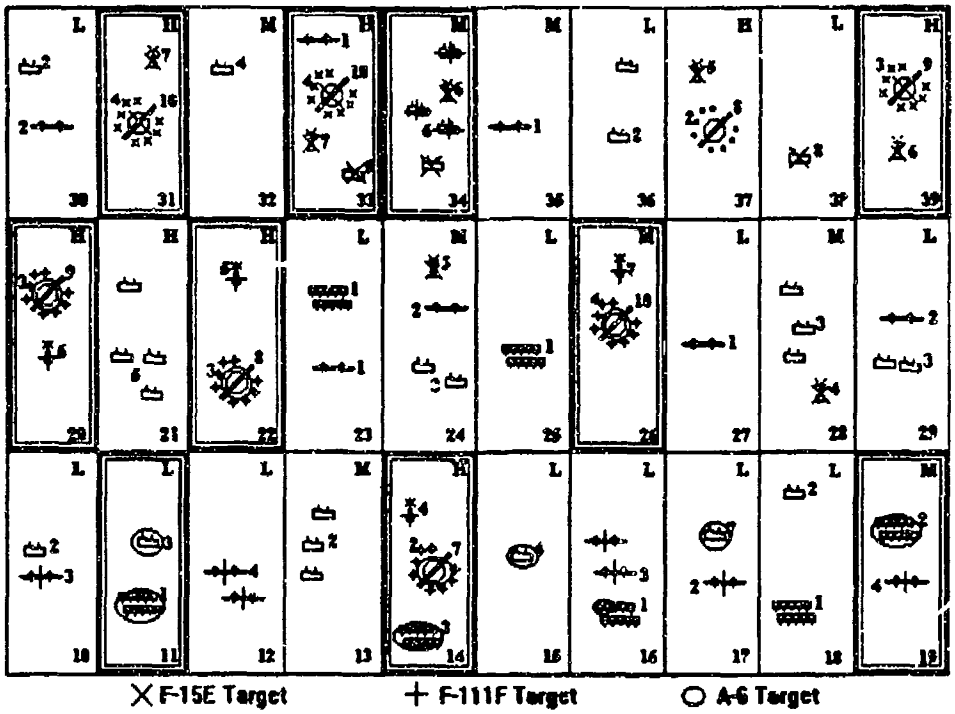

Figure 4-3. Strike Package and Targeting Plan

therefore, unsupported packages would contain more aircraft.) The aircraft that did not receive escort or SEAD either had high PSA and PSG values or were sent to low threat target locations. In all cases the model chose the weapons with the highest PK for each aircraft and target combination. It also used every available aircraft, and it assigned attackers to most of the high value targets. The model made some tradeoffs where lower value targets with a reduced threat could be attacked instead of high value targets with an associated high threat level. An example of this tradeoff occurred in sectors 21 and 22. All of the 3-point HASs were targeted in 22 where SEAD and escort reduced the threat level, while none of the 5-point factories in 21 were targeted. Another type of tradeoff occurred in sector 37, where the 5-point

command center was targeted instead of the 8-point runway because the latter required many more aircraft to destroy.

4.1.2 Sensitivity to Attrition Weighting. The MIP for this last example had an attrition penalty (*W*) of fifty, which is five times the maximum target value. This section discusses the results of changing *W* from 0 to 100 using the same example.

When *W* is zero the model strictly maximizes expected target value destroyed. SEAD and air-to-air escort aircraft only serve to decrease PSA and PSG in such a manner that expected TVD is higher, not necessarily minimizing expected attrition.

As *W* increases, the model attempts to allocate SEAD and escort more effectively, giving more vulnerable aircraft protection, and avoiding higher threat sectors without SEAD and escort coverage. The expected TVD decreases gradually as *W* increases. TVD decreases a total of 10.6 percent from its value at *W* equal to 0. Expected attrition also goes down as *W* increases. With *W* equal to 0, expected attrition for a 6 hour period is 2.2 aircraft. At *W* equal to 100 the expected attrition is 1.5, a decrease of about 30 percent. This change may seem small, but when considered over the course of the entire war, such a change becomes significant. The solutions are summarized in Figure 4-4 .[2]

The last point on the right side of Figure 4-4 is the result of restructuring the algorithm to minimize EA without regard to TVD. For this solution the model was

[2] The MIP solutions in Figure 4-4 were all within 3 percent of the relaxed MIP optimum, but variations occurred within this 3 percent. As a result the smoothness of the curve for *EA* was affected somewhat by the degree of optimality for each solution. For instance, at *W* equal to forty the solution was not as close to fully optimal as the previous solution, so *EA* appears to level off.

constrained to use all available aircraft. The result was that EA decreased at the expense of much TVD. Furthermore, the model allocated aircraft to only the lowest threat sectors and chose munitions with low PKs to allow more aircraft into packages with SEAD and escort.

The MIP in Section 4.1.1 used *W* set at fifty. This value was chosen because TVD was fairly high (1 percent less than the TVD at *W* equal to 0) and because attrition was significantly lower (14 percent less than the attrition at *W* equal to 0). Increasing *W* even more is feasible, but left to the user's discretion. For example, with *W* at 100 the model determined that expected attrition was not worth the expected TVD in some cases, and as a result, it did not use 20 of the 50 A-6s.

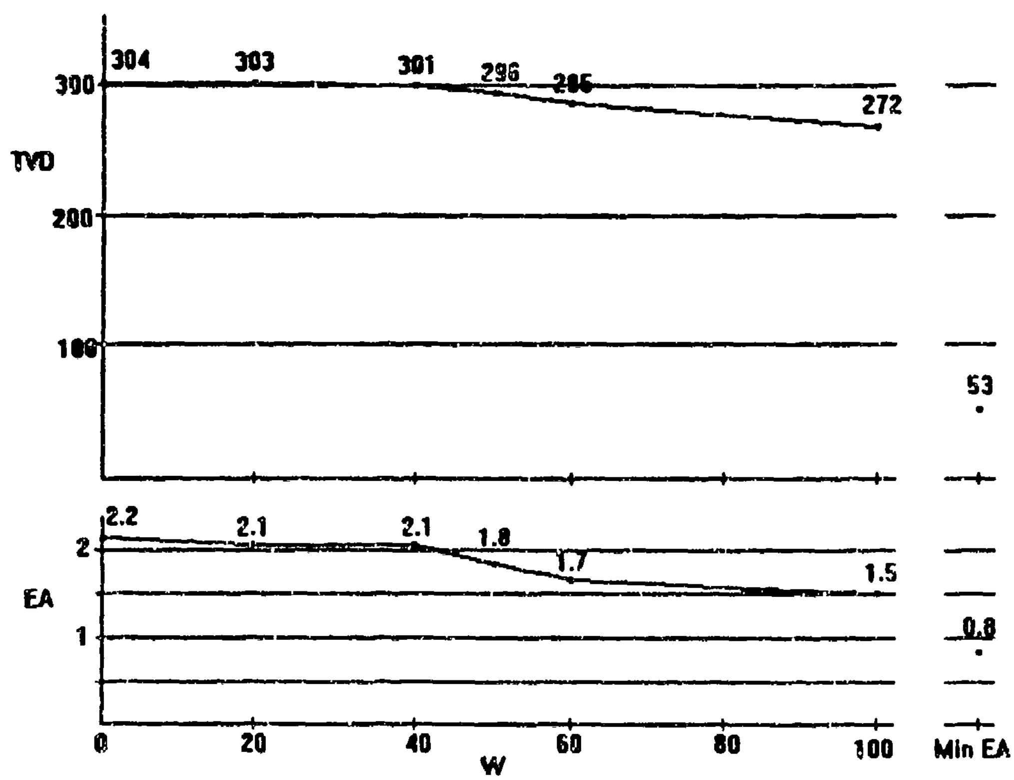

Figure 4-4. Target Value Destroyed (TVD) and Expected Attrition (EA) vs Attrition Penalty (W)

4.1.3 Sensitivity to Solution Methods. Section 3.2.3 showed a rule set (Method 2 below) which allowed a non-integer solution for the model requiring a simpler solver and resulting in quicker solution times. This section discusses the results of applying various rules sets while using a continuous variable LP solver, the GAMS/MINOS (11)(16) package.

The following list shows the various solution methods tested:

Method 1. Use the MIP from Section 4.1.1 and run it to optimality as a reference.

Method 2. a. Use the relaxed MIP (with 0 or 1 constraints relaxed to $0 \leq Y \leq 1$) to obtain a continuous variable solution for SEAD and air-to-air escort allocation.

b. Take the highest fractional solutions for SEAD and escort allocation and increase them to one.

c. Run the model as an LP with SEAD and escort assigned as per step b. (See Appendix B for notes on this LP.)

Method 3. a. Assign SEAD and escort to sectors with the highest target values.

b. Run the model as an LP with SEAD and escort assigned as per step a.

Method 4. a. Use the relaxed MIP to obtain a continuous variable solution for SEAD and air-to-air escort allocation.

b. Assign SEAD and escort to the sectors chosen in step a with the highest target value.

c. Run the model as an LP with SEAD and escort assigned as per step b.

Method 5. a. Use the relaxed MIP continuous variable solution for SEAD and air-to-air escort allocation.

b. Assign SEAD and escort to the sectors chosen in step a with the highest target values. Assign based on high threat first, medium threat next, and low threat last.

c. Run the model as an LP with SEAD and escort assigned as per step b.

The results of the tests indicate that the objective value, expected attrition, and target value destroyed are relatively insensitive to the solution method, but the time to solve decreases dramatically for the non-integer methods. See Figure 4-5.

Of all the non-integer methods, Method 2 obtained the best objective value, while solving the program in less than half the time of the MIP solver. Method 3 was the fastest because it did not use the relaxed MIP solution. The drawback to Method 3 is that its objective value was the lowest of all three methods.

4.2 Phase II: Handling the Weather

Effective weather planning is essential for flying operations. Failing to account for uncertainty in weather phenomena can result in wasted missions, unnecessary exposure to enemy defenses, and unfulfilled campaign objectives. Since employment of some munitions requires certain minimum ceilings and visibilities, adverse weather can force sorties using these munitions to either drop smart weapons in their "dumb" mode or to bring their weapons back after needless exposure to enemy threats. On the other hand, using all-weather munitions when precision munitions will work can delay accomplishment of campaign objectives because of the reduced accuracy of most all-weather munitions. The following sections illustrate the effectiveness of using decision trees to handle the uncertainty of weather and forecasts.

4.2.1 A Decision Tree Without a Forecast. Mission planners could make tasking decisions without the use of a weather forecast. Figure 4-6 shows a tree using only prior probabilities about the weather and no forecast. By solving Phase I for each weather state, the mission planner can solve the decision tree using the weather algorithm from Section 3.3. For the munitions in this example, it was assumed that

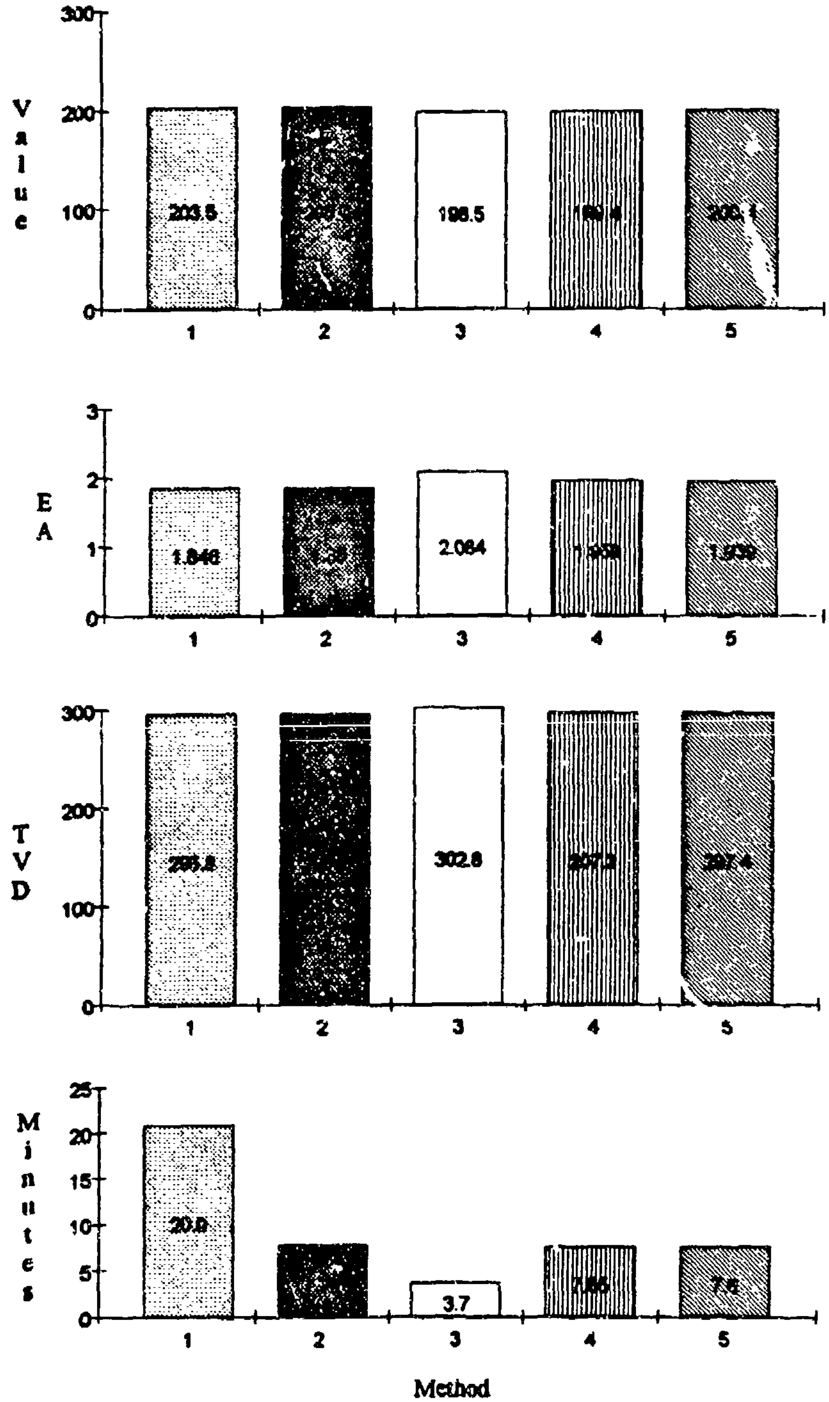

Figure 4-5. Comparison of Solution Methods

the GBU-10s require good weather, Mavericks require marginal or good weather, and Durandals and MK-82s can be dropped in any weather. Using the example from Section 4.1, the weather algorithm provided values for each branch of the decision tree. If the planner sent out a good weather ATO on this day, he could expect to obtain a value of 108.8. If he used the marginal weather ATO, his expected value would be 119.4, and so on. To maximize expected value in this case, the planner would use the marginal weather ATO.

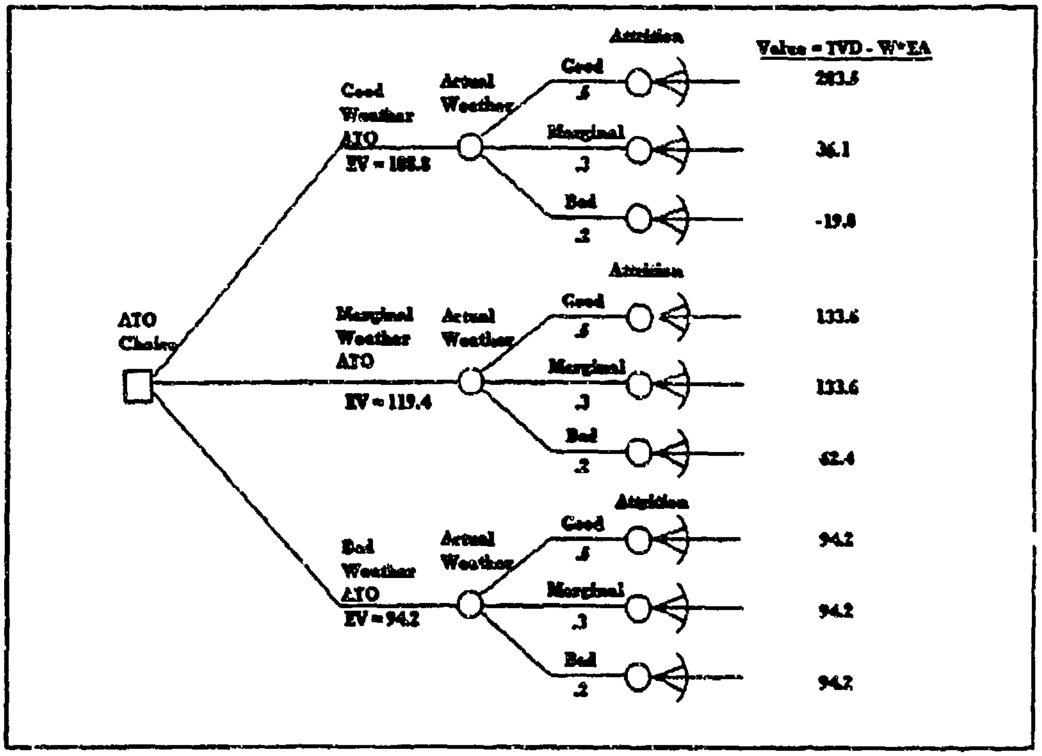

Figure 4-6. Decision Tree Without a Weather Forecast

4.2.2 A Decision Tree With a Forecast. The decision tree in Figure 4-7 provides a means of handling the uncertainty of weather and weather forecasts during the mission planning process. The concept of the expected value of sample

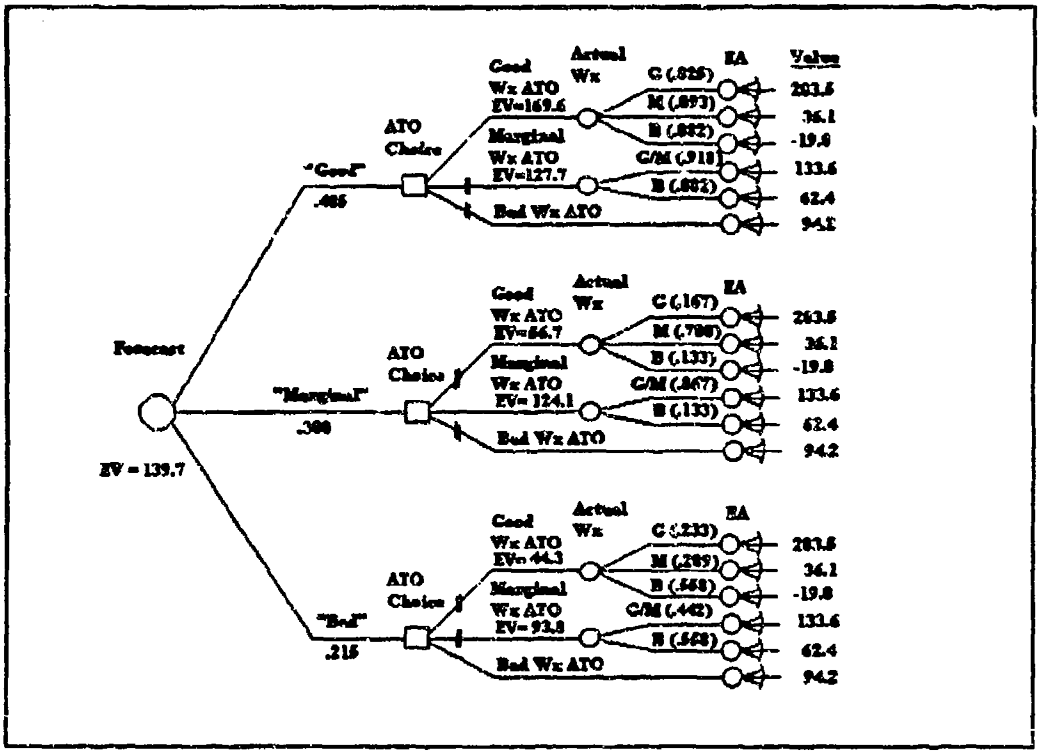

Figure 4-7. Decision Tree With a Weather Forecast (4:350)

information (EVSI) can demonstrate the value of using this decision tree (4:350). Using the same prior probabilities as Figure 4-6, and the conditional probabilities given in Table 4-3, Figure 4-7 shows the resulting decision tree. If the mission planner maximized expected value for each forecast, his expected value would be 139.7. Thus, the EVSI would be 139.7 - 119.4 = 20.3. In other words, the mission planner would gain about 20 value points over the previous tree, an improvement of 17 percent.

Although Figure 4-7 indicates that the mission planner should simply choose the ATO that matches the forecast, this is not always the case. Different probabilities and different ATO values can change the decision. The planner must solve the weather

decision tree for each six hour period of the war in order to maximize expected value.

Table 4-3. Probability of Forecast Given Actual Weather (4:345).

	Actual Weather		
Forecast	Good	Marginal	Bad
"Good"	.8	.15	.2
"Marginal"	.1	.7	.2
"Bad"	.1	.15	.6

4.2.3 A Decision Tree With Perfect Information. If mission planners had access to perfect weather information, they would know with certainty when the weather would be in each state. As a result, they could pick the correct ATO each time. The expected value for the previous case with perfect information would be 160.7. The expected value of this perfect weather information would be

160.7 - 119.4 = 41.3. So, if planners had perfect weather information, they could gain about 41 value points more than if they had only prior probabilities, an improvement of 34 percent.

4.2.4 Summary of the Weather Algorithm. Data will most likely be available for the decision tree in Figure 4-7. This decision tree maximizes expected value for the given forecast. For each tasking period the user must run three Phase I programs and apply the heuristics from Table 3-1 to solve the decision tree for the given weather forecast.

V. RECOMMENDATIONS

The following sections provide recommendations for implementing the strike package algorithms into the FTLM. Suggestions are made for adjusting the attrition penalty, selecting the solver, and sizing the target grid. Use of the algorithms will also require some follow-on work which is listed in Section 5.4. Last, an interface control diagram shows how the strike package planner will link into the FTLM.

5.1 Attrition Penalty

Different theaters will require different attrition penalties (*W*). Each theater, having various enemy SAMs, AAA, and interceptors, will have a unique set of probabilities of survival against the air and ground threats (PSA and PSG). If these probabilities are very close to one, such as in Iraq, the attrition penalty will have very little effect at low values. The situation will reflect the curve in Figure 4-4, where *W* ranges from zero to about twenty; ie, neither TVD nor EA will change much. On the other hand, with lower PSA and PSG probabilities, lower attrition penalties will have a greater effect because EA will be greater. For this reason each theater will require an adjusted value of *W*.

Additionally, the user might want to change *W* for political reasons. For instance, in WWII American air forces had a maximum acceptable attrition rate of 10 percent (20:60). In contrast, attrition was much less acceptable in the Gulf War. This led to an attrition rate in the Gulf of only .00047 aircraft losses per sortie (9:34). For the political climate of the Gulf War the user might want attrition penalties on the

higher end of the scale. For a global war, planners might want penalties near zero.

As an upper bound for W, the user should consider the point at which the model starts to leave aircraft on the ground instead of flying all of them. At this point the attrition penalty is so high that more vulnerable aircraft cannot gain enough TVD to justify their expected level of attrition. Again, this situation might still be acceptable given some political scenarios.

In summary, the user must choose an attrition penalty that is appropriate for the enemy's defensive capabilities and reflects the current political climate.

5.2 Solution Method

Figure 4-5 shows that the objective value for each method was almost the same. Therefore, no matter what solution method the user prefers, the results for EA and TVD should be close.

The biggest difference between methods was solution times: the MIP solution was slowest while Method 3 took about one-fifth as much time. As a result, the user should consider his available solving time when deciding on the method.

Another major difference between solution methods was that Method 1 used an integer solver, and the others used continuous variable LP solvers. Integer solvers generally become slower and less reliable with an increase in the number of integer decision variables. So if the user increases the number of sectors beyond thirty, the number used in Figure 4-5, then even longer solving times will occur. Of course, more powerful computers and specialized algorithms can mitigate this problem, but the FTLM user should carefully consider solver cost and computing power available when choosing the solution method.

The user should consider using Method 2. It provided excellent solutions in a relatively short time. Of all the LP methods it had the highest objective value and lowest expected attrition. Given that the model had a total of about 17,000 decision variables and a full-scale scenario might have 1 to 2 million decision variables, the full scale scenario might magnify small differences in EA and TVD from the smaller case. Method 2 offers the speed and simplicity from the LP solver, and yet it provides solutions nearly as good as the MIP solution.

5.3 Target Grid

The FTLM user must design a target grid for each theater. Aspects to consider for the grid include sector size, location, and number of sectors.

The number of targets enclosed by a sector in the grid will determine the maximum number of aircraft that the model can assign to an air strike package going to that sector. Sectors with many targets can receive very large packages while sectors with few targets will receive small packages. For this reason, the user should carefully consider the size and geographic location of each sector to avoid excessively large or small strike packages. In actual operations, coordination problems and SEAD duration keep package sizes down, while the desire for mass and mutual support pushes package sizes up. MCM 3-3 suggests a maximum of about ninety aircraft per package.

The number of sectors also determines strike package size. For instance, as in Figure 4-3, a large number of sectors for a relatively small number of aircraft will allow small strike packages. In contrast, using few sectors with many targets and many aircraft will produce large strike packages. Again, the maximum size of

packages should be kept to the limits set by MCM 3-3.

Sectors can cover any location in the theater as long as they are within range of one of the types of attacking aircraft. Also, sectors do not need to be adjacent to one another. For simplicity of aircraft range constraints, sector depths should reflect aircraft combat radii. For instance, the first row should contain targets accessible to short range fighters, and the last row should contain targets accessible to long range fighters. The row or rows in between should reflect medium range fighter capabilities. Column borders can be adjusted to enclose the appropriate number of targets.

5.4 Follow-On Work

Several topics lend themselves to follow on study. These areas include a means of prioritizing and placing values on targets to reflect campaign objectives, a means of choosing PSA and PSG data for each aircraft type against perceived threat arrays, and a mission scheduling program. In addition, the model requires research on weather data and expansion to full-scale.

The target prioritization phase shown in Figure 2-1 should transform campaign objectives into values for the set of targets perceived by intelligence and reconnaissance sources. These target values should also reflect uncertainties in the intelligence and reconnaissance perceptions. For instance, if the identity of a target is uncertain, then an expected target value might be used reflecting the probabilities and values of each possible target type for the ambiguous target. The current model relies on values set between one and ten. The user can change this range, but he must also change the attrition penalty correspondingly. In any event, the FTLM requires a target value list from a rule set or algorithm which provides reasonable target values.

The model also requires a processor to select PSA and PSG data appropriate for the perceived air and surface threats in the theater. The processor which chooses PSA and PSG must account for uncertainties in the perceptions of threats in order to properly interface with the FTLM architecture. Each aircraft type will require values for PSA and PSG for the proposed routes to each sector. PSA and PSG must also reflect benefits when SEAD or air-to-air escort packages protect the aircraft.

The FTLM also needs a mission scheduling program to coordinate takeoffs, refuelling times and TOTs. Coordination should prevent back-ups on tankers, allow deconfliction in the target area, and provide time for all aircraft assigned to a package to get together before penetrating enemy airspace.

Next, the model requires weather data for each theater of interest. Specifically, the air mission planner needs conditional probabilities for actual weather states given the forecasts.

Last, expanding the model to full-scale will bring to light problems associated with the addition of new aircraft, munitions, and targets. So far, attacking aircraft have been allocated to only one target per sortie. Assigning a single aircraft with many high PK weapons to multiple targets is a subject worth exploring. Likewise, employment of stand-off munitions might also require some changes. For instance, adding a munitions index (m) to PSG_{arct} should allow for increased survivability benefits from stand-off munitions. While many concepts are worth exploring, the researcher must remember that the top down design approach requires keeping the level of detail to the lowest level compatible with the purpose of the model.

5.5 Interface Control

The target evaluation phase, strike package planner, route selector, and scheduling program must interface effectively to complete the air planning portion of the FTLM. Figure 5-1 depicts a proposed arrangement of these planning functions. Previous sections have already described the functions of many of the blocks in the figure, except for the route planner, munitions counter, and aircraft counter.

The route planner must determine the best route to each sector, minimizing the perceived threat and staying within the range constraints of attackers. In addition, it must also determine the best flight altitudes for threat minimization. Finally, the routing program must supply its routes and enroute times to the scheduling program.

The aircraft counter must feed data to the strike package builder. The counter should decrement for attrition and increment for new squadrons in theater. It must also parcel out aircraft capable of night operations during the two night tasking periods and aircraft restricted to day operations during the two day periods.

The munitions counter must track all munitions in the theater. The counter should be initialized for all munitions existing in the theater at the start of the conflict. It should then increment for incoming munitions and decrement for outgoing munitions. It should also increment for aircraft returning with unexpended munitions. Finally, since aircraft squadrons will only have access to munitions at their own bases, the counter must also determine which munitions are available for which aircraft types.

The munitions counter, the aircraft counter, and the threat processor, along with the other functions in Figure 5-1, should handle the majority of tactical air planning in theater. Of course, the FTLM creators must still add the entire logistics mechanism.

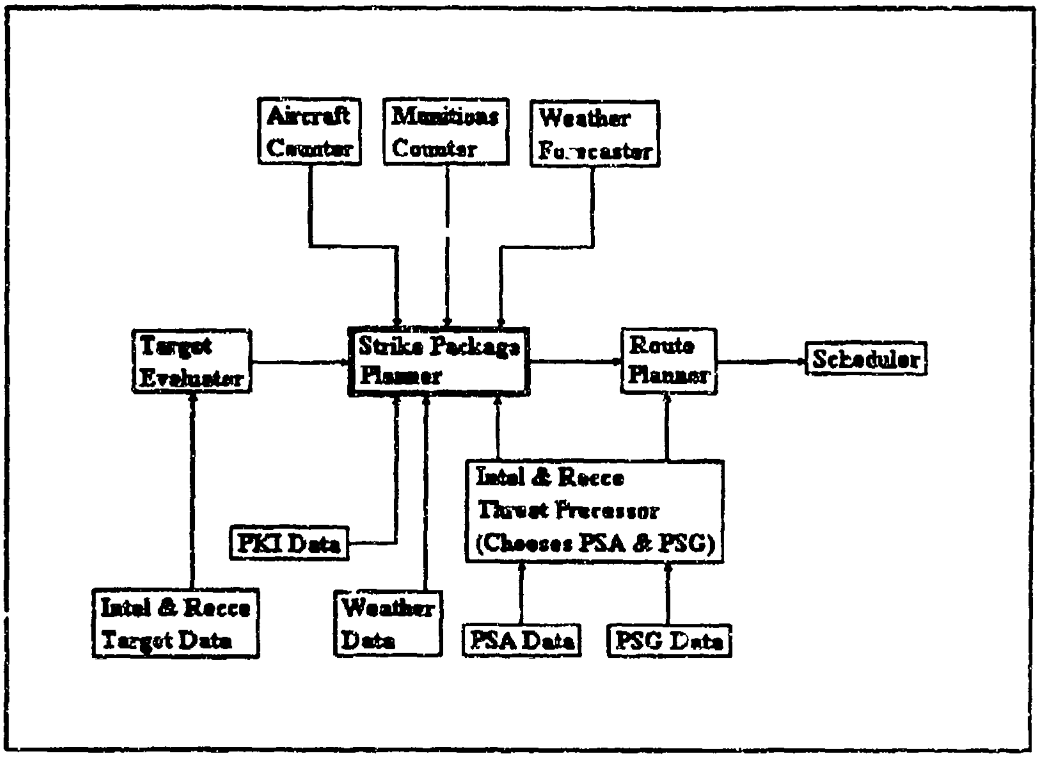

Figure 5-1. Interface Control Diagram

5.6 Conclusion

The proposed air strike package planner will provide realistic aircraft packages for the FTLM. Phase I supplies the optimum degree of force for each campaign objective by allocating the optimum number and type of aircraft and munition against each target. In addition, Phase I takes advantage of the force multiplying effects of mass and mutual support through its use of strike packages with SEAD and air-to-air escort. Finally, Phase II effectively handles the uncertainties of weather and weather forecasts. The algorithms in Phase I and II omit many of the details in the actual aircraft tasking process, but provide fast, nearly optimal solutions which should approximate real world tasking results.

APPENDIX A. GAMS MIXED INTEGER PROGRAM

A.1 GAMS Index Definitions

Each decision variable *x* includes the following indices. The GAMS solution on the next page shows the level of each variable defined by these indices.

A1: F-15E
A2: F-111F
A3: A-6

M1: Mark 82 General Purpose Bomb
M2: Durandal Runway Cratering Munition
M3: AGM-65 Maverick Air-to-Surface Missile
M4: GBU-10 Laser Guided Bomb

T1: Hardened Aircraft Shelter
T2: Runway
T3: Command Center
T4: Factory
T5: Bridge
T6: Tank

P6: Desired PK of .6
P8: Desired PK of .8

R1-R3: rows
C0-C9: columns

E1: with air-to-air escort
E0: without air-to-air escort

S1: with SEAD
S0: without SEAD

A.2 GAMS Solution

Decision Variable Indices	Level
A1.M1.P6.T4.R3.C3.E1.S1	1
A1.M1.P6.T4.R3.C4.E1.S1	1.5
A1.M1.P6.T4.R3.C8.E0.S0	1
A1.M2.P6.T2.R3.C1.E1.S1	1
A1.M2.P6.T2.R3.C3.E1.S1	1
A1.M2.P6.T2.R3.C9.E1.S1	1
A1.M4.P6.T1.R3.C1.E1.S1	8
A1.M4.P6.T1.R3.C3.E1.S1	8
A1.M4.P6.T1.R3.C9.E1.S1	8
A1.M4.P6.T3.R2.C4.E0.S0	1
A1.M4.P6.T3.R2.C8.E0.S0	1
A1.M4.P6.T3.R3.C7.E0.S0	1
A1.M4.P6.T3.R3.C9.E1.S1	1
A1.M4.P8.T3.R3.C1.E1.S1	1
A1.M4.P8.T3.R3.C3.E1.S1	1
A1.M4.P8.T3.R3.C4.E1.S1	1
A2.M1.P6.T4.R3.C4.E1.S1	2.5
A2.M4.P6.T1.R1.C4.E1.S1	8
A2.M4.P6.T1.R2.C0.E1.S1	8
A2.M4.P6.T1.R2.C2.E1.S1	8
A2.M4.P6.T1.R2.C6.E1.S1	8
A2.M4.P6.T3.R1.C4.E1.S1	1
A2.M4.P6.T3.R2.C2.E1.S1	1
A2.M4.P6.T5.R1.C0.E0.S0	1
A2.M4.P6.T5.R1.C2.E0.S0	2
A2.M4.P6.T5.R1.C6.E0.S0	2
A2.M4.P6.T5.R1.C7.E0.S0	1
A2.M4.P6.T5.R1.C9.E1.S1	1
A2.M4.P8.T3.R2.C0.E1.S1	1
A2.M4.P8.T3.R2.C6.E1.S1	1
A3.M1.P6.T4.R1.C1.E1.S1	1
A3.M1.P6.T4.R1.C5.E0.S0	1
A3.M1.P6.T4.R1.C7.E0.S0	1
A3.M2.P6.T2.R1.C4.E1.S1	1
A3.M2.P6.T2.R2.C0.E1.S1	1
A3.M2.P6.T2.R2.C2.E1.S1	1
A3.M2.P6.T2.R2.C6.E1.S1	1
A3.M3.P8.T6.R1.C1.E1.S1	10
A3.M3.P8.T6.R1.C4.E1.S1	10
A3.M3.P8.T6.R1.C6.E0.S0	2
A3.M3.P8.T6.R1.C9.E1.S1	10

Objective Value = 203.5191
Relaxed LP Value = 203.89918
Expected Attrition = 1.846
Expected TVD = 295.837
Total Time = 20:54

A.3 GAMS Mixed Integer Program

```
$OFFSYMXREF OFFSYMLIST

SETS
        A aircraft types  /  A1 * A3/
        M munitions       /  M1 * M4/
        P desired PK      /  P6, P8/
        T target types    /  T1 * T6/
        R row or distance /  R1, R2, R3/
        C column          /  C0 * C9/
        E escort          /  E1, E0/
        S sead            /  S1, S0/;

SCALAR W weight of penalty for loss of one aircraft /50/;

TABLE PKI(A,M,T) probability of kill for individual aircraft

          T1    T2    T3    T4    T5    T6
  A1.M1   .4    .2    .3    .4    .3
  A1.M2   .2    .3    .1    .2    .2
  A1.M3
  A1.M4   .6    .2    .6    .4    .6    .4
  A2.M1   .3    .2    .2    .4    .3
  A2.M2   .2    .3    .1    .2    .2
  A2.M3
  A2.M4   .6    .2    .6    .4    .6    .4
  A3.M1   .3    .2    .2    .4    .3
  A3.M2   .2    .3    .1    .2    .2
  A3.M3                                   .9
  A3.M4                                    ;

TABLE N(A,M,P,T) aircraft required to achieve desired destruction

             T1    T2    T3    T4    T5    T6
  A1.M1.P6   2     5     3     2     3     60
  A1.M1.P8   4     8     5     4     5     60
  A1.M2.P6   5     3     9     5     5     60
  A1.M2.P8   8     5     16    8     8     60
  A1.M3.P6   60    60    60    60    60    60
  A1.M3.P8   60    60    60    60    60    60
  A1.M4.P6   1     5     1     2     1     2
  A1.M4.P8   2     8     2     4     2     4
  A2.M1.P6   3     5     5     2     3     60
  A2.M1.P8   5     8     8     4     5     60
```

A2.M2.P6	5	3	9	5	5	60
A2.M2.P8	8	5	16	8	8	60
A2.M3.P6	60	60	60	60	60	60
A2.M3.P8	60	60	60	60	60	60
A2.M4.P6	1	5	1	2	1	2
A2.M4.P8	2	8	2	4	2	4
A3.M1.P6	3	5	5	2	3	60
A3.M1.P8	5	8	8	4	5	60
A3.M2.P6	5	3	9	5	5	60
A3.M2.P8	8	5	16	8	8	60
A3.M3.P6	60	60	60	60	60	60
A3.M3.P8	60	60	60	60	60	1
A3 M4.P6	60	60	60	60	60	60
A3.M4.P8	60	60	60	60	60	60 ;

TABLE PSA(A,R,E) probability of survival due to air threat

	E1	E0
A1.R1	.9980	.9960
A1.R2	.9960	.9920
A1.R3	.9940	.9880
A2.R1	.9965	.9930
A2.R2	.9930	.9860
A2.R3	.9895	.9790
A3.R1	.9955	.9910
A3.R2	.9910	.9820
A3.R3		

;

TABLE PSG(A,R,C,S) probability of survival due to ground threat

	S1	S0
A1.R1.C0	.999	.998
A1.R1.C1	.999	.998
A1.R1.C2	.999	.998
A1.R1.C3	.998	.995
A1.R1.C4	.995	.990
A1.R1.C5	.999	.998
A1.R1.C6	.999	.998
A1.R1.C7	.999	.998
A1.R1.C8	.999	.998
A1.R1.C9	.998	.995
A1.R2.C0	.995	.990
A1.R2.C1	.995	.990
A1.R2.C2	.995	.990
A1.R2.C3	.999	.998

A1.R2.C4	.998	.995
A1.R2.C5	.999	.998
A1.R2.C6	.998	.995
A1.R2.C7	.999	.998
A1.R2.C8	.998	.995
A1.R2.C9	.999	.998
A1.R3.C0	.999	.998
A1.R3.C1	.995	.990
A1.R3.C2	.998	.995
A1.R3.C3	.995	.990
A1.R3.C4	.998	.995
A1.R3.C5	.998	.995
A1.R3.C6	.999	.998
A1.R3.C7	.995	.990
A1.R3.C8	.999	.998
A1.R3.C9	.995	.990
A2.R1.C0	.998	.996
A2.R1.C1	.998	.996
A2.R1.C2	.998	.996
A2.R1.C3	.996	.992
A2.R1.C4	.992	.985
A2.R1.C5	.998	.996
A2.R1.C6	.998	.996
A2.R1.C7	.998	.996
A2.R1.C8	.998	.996
A2.R1.C9	.996	.992
A2.R2.C0	.992	.985
A2.R2.C1	.992	.985
A2.R2.C2	.992	.985
A2.R2.C3	.998	.996
A2.R2.C4	.996	.992
A2.R2.C5	.998	.996
A2.R2.C6	.996	.992
A2.R2.C7	.998	.996
A2.R2.C8	.996	.992
A2.R2.C9	.998	.996
A2.R3.C0	.998	.996
A2.R3.C1	.992	.985
A2.R3.C2	.996	.992
A2.R3.C3	.992	.985
A2.R3.C4	.996	.992
A2.R3.C5	.996	.992
A2.R3.C6	.998	.996
A2.R3.C7	.992	.985
A2.R3.C8	.998	.996

A2.R3.C9	.992	.985
A3.R1.C0	.997	.994
A3.R1.C1	.997	.994
A3.R1.C2	.997	.994
A3.R1.C3	.994	.989
A3.R1.C4	.989	.978
A3.R1.C5	.997	.994
A3.R1.C6	.997	.994
A3.R1.C7	.997	.994
A3.R1.C8	.997	.994
A3.R1.C9	.994	.989
A3.R2.C0	.989	.978
A3.R2.C1	.989	.978
A3.R2.C2	.989	.978
A3.R2.C3	.997	.994
A3.R2.C4	.994	.989
A3.R2.C5	.997	.994
A3.R2.C6	.994	.989
A3.R2.C7	.997	.994
A3.R2.C8	.994	.989
A3.R2.C9	.997	.994
A3.R3.C0		
A3.R3.C1		
A3.R3.C2		
A3.R3.C3		
A3.R3.C4		
A3.R3.C5		
A3.R3.C6		
A3.R3.C7		
A3.R3.C8		
A3.R3.C9		;

TABLE TVAL(T,R,C) target values

	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
T1.R1					2					
T1.R2	3		3				4			
T1.R3		4		4				2		3
T2.R1					7					
T2.R2	9		8				10			
T2.R3		10		10				8		9
T3.R1					4					
T3.R2	6		5		5		7		4	
T3.R3		7		7	6			5		6
T4.R1	2	3		2		4		7	2	

	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
T4.R2		5			3				3	3
T4.R3	2		4	5	6		2		8	
T5.R1	3		4				3	2		4
T5.R2				1	2			1		2
T5.R3	2			1		1				
T6.R1		1			3		1		1	2
T6.R2				1		1				
T6.R3										;

TABLE NTGT(R,C) targets per sector total 196

	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
R1	2	11	2	3	20	1	12	2	11	11
R2	10	4	10	11	4	10	10	1	4	3
R3	2	10	1	12	5	1	2	10	1	10;

TABLE NTYPE(T,R,C) number of targets by type in each sector

	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
T1.R1					8					
T1.R2	8		8				8			
T1.R3		8		8				8		8
T2.R1					1					
T2.R2	1		1				1			
T2.R3		1		1				1		1
T3.R1					1					
T3.R2	1		1		1		1		1	
T3.R3		1		1	1			1		1
T4.R1	1	1		3		1		1	1	
T4.R2		4			2				3	2
T4.R3	1		1	1	4		2		1	
T5.R1	1		2				2	1		1
T5.R2				1	1			1		1
T5.R3	1			1		1				
T6.R1		10			10		10		10	10
T6.R2					10		10			
T6.R3										;

PARAMETER NUMAC(A) number of aircraft of each type
/A1 50
A2 50
A3 50/;

```
PARAMETER  PKT(A,M,P,T,R,C,E,S)  total probability of kill for a formation;
   PKT(A,M,P,T,R,C,E,S) =
      1-(1-PSA(A,R,E)*PSG(A,R,C,S)*PKI(A,M,T))**N(A,M,P,T);

PARAMETER  EA(A,M,P,T,R,C,E,S)  expected attrition for a formation;
   EA(A,M,P,T,R,C,E,S) = (1 - PSA(A,R,E)*PSG(A,R,C,S))*N(A,M,P,T);

VARIABLES
   X(A,M,P,T,R,C,E,S)  number of flights
   VAL  target value destroyed less attrition penalty
   SP(R,C)  sead packages
   EP(R,C)  escort packages
   ATTR  expected attrition
   TVD  target value destroyed;

POSITIVE VARIABLE  X;
BINARY VARIABLE  SP;
BINARY VARIABLE  EP;

EQUATIONS
         VALUE  define objective function
         AIRCRAFT(A)  available aircraft by type
         ESCPACK(R,C)  available escort packages
         SEADPACK(R,C)  available sead packages
         TARGETS(T,R,C)  hit each target only once
         ESCTOT  total escort packages
         SEADTOT  total sead packages
         ATTOT  total expected attrition
         TVDTOT  total tvd;

VALUE..VAL =E= SUM((A,M,P,T,R,C,E,S), X(A,M,P,T,R,C,E,S)*
        (PKT(A,M,P,T,R,C,E,S)*TVAL(T,R,C) - EA(A,M,P,T,R,C,E,S)*W));

AIRCRAFT(A)..SUM((M,P,T,R,C,E,S), X(A,M,P,T,R,C,E,S)*N(A,M,P,T)) =L=
      NUMAC(A);

ESCPACK(R,C)..SUM ((A,M,P,T,S), X(A,M,P,T,R,C,'E1',S)) =L=
      NTGT(R,C)*EP(R,C);

SEADPACK(R,C)..SUM ((A,M,P,T,E), X(A,M,P,T,R,C,E,'S1')) =L=
      NTGT(R,C)*SP(R,C);

TARGETS(T,R,C)..SUM ((A,M,P,E,S), X(A,M,P,T,R,C,E,S)) =L= NTYPE(T,R,C);

ESCTOT .. SUM ((R,C), EP(R,C)) =E= 10;
```

```
SEADTOT .. SUM ((R,C), SP(R,C)) =E= 10;

ATTOT..ATTR=E=SUM((A,M,P,T,R,C,E,S),X(A,M,P,T,R,C,E,S)*
  EA(A,M,P,T,R,C,E,S));

TVDTOT..TVD=E=SUM((A,M,P,T,R,C,E,S), X(A,M,P,T,R,C,E,S)*
        (PKT(A,M,P,T,R,C,E,S)*TVAL(T,R,C)));

MODEL NEW17IW5 /ALL/;
OPTION OPTCR=.002, LIMROW=0, LIMCOL=0, ITERLIM=1000000,
     WORK=1000000, RESLIM=100000;
SOLVE NEW17IW5 USING MIP MAXIMIZING VAL;
DISPLAY X.L, EP.L, SP.L;
```

APPENDIX B. GAMS LINEAR PROGRAM

To change the integer program in Appendix A into a continuous variable LP, the user must eliminate *EP* and *SP* as decision variables. To accomplish this, the user must assign SEAD and escort packages using one of the heuristic methods from Section 4.1.3. Next, the GAMS MIP can be modified to run as a continuous variable program with the following steps:

1. Add two tables for SEAD and escort assignments, one for EP_{rc} and the other for SP_{rc}. The tables will look like this:

TABLE EP(R,C) escort package assignments

	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
R1					1					
R2	1	1	1				1			
R3		1		1	1			1		1

2. Delete "EP(R,C)" and "SP(R,C)" under "VARIABLES".

3. Delete the statements "BINARY VARIABLE SP" and "BINARY VARIABLE EP".

4. Delete "ESCTOT" and "SEADTOT" under "EQUATIONS". Then delete the corresponding equations.

5. In the solve statement replace "MIP" with "LP".

6. In the display statement delete "EP.L" and "SP.L".

The resulting program is a continuous variable LP.

BIBLIOGRAPHY

1. Air Force Studies and Analysis Agency. *TAC Thunder Analyst's Manual.* Version 5.8. Arlington VA: CACI Products Company, October 1992.

2. ATRC-FMV, TACWAR Project Officer. *TACWAR Air Analyst's Guide.* Version 3.3. Fort Leavenworth KS. TRAC-OAC, July 1993.

3. Bennett, Bruce W. and others. *RSAS 5.2 Summary.* Santa Monica CA: RAND, 1993.

4. Clemen, Robert T. *Making Hard Decisions.* Boston: PWS-KENT Publishing Company, 1991.

5. Cotsworth, William. AEM Services, Englewood CO. Telephone interview. 4 October 1993.

6. Cotsworth, William. AEM Services, Englewood CO. Correspondence, 2 December 1993.

7. Department of the Air Force. *Basic Aerospace Doctrine of the United States Air Force.* AFM 1-1, Volume II. Washington: HQ USAF, March 1992.

8. Department of the Air Force. *Mission Employment Tactics, Fighter Fundamentals, F-111.* MCM 3-3. Langley AFB VA: HQ TAC, 1 August 1990.

9. Department of the Air Force. *Reaching Globally, Reaching Powerfully: The United States Air Forces in the Gulf War.* Washington: Government Printing Office, 1991.

10. Dombroski, Ann, Lt, USAF. Aeronautical Systems Command, Wright-Patterson AFB OH. Personal interview. 4 October 1993.

11. GAMS. Version 2.20, VMS System. Computer Software. Boyd and Fraser Publishing Co. Danvers MA, 1988.

12. Jackson, Jack A., Jr. *A Taxonomy of Advanced Linear Programming Techniques and the Theater Attack Model.* MS Thesis, AFIT/GST/ENS/89M-7. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 1989. (AD - A205847).

13. Lynch, Frank. STR Corporation, Reston VA. Telephone interview. 7 October 1993.

14. McCrabb, Maris, LtCol, USAF. "Air Campaign Planning," *Airpower Journal*: 11-22 (Summer 1993)

15. Meyer, Scott K. "Top-Down Modeling," *The Executive Analyst*, 1(2): 1-8 (1987).

16. MINOS. Version 5.2, VMS System. Computer Software. Boyd and Fraser Publishing Co. Danvers MA, 1988.

17. Moore, Louis. Rand, Santa Monica CA. Telephone interview. 7 October 1993.

18. Owen, John. Rand, Santa Monica CA. Telephone interview. 8 October 1993.

19. Venttsel, Ye. S. *Introduction to Operations Research*. Moscow: Soviet Radio Publishing House, 1964.

20. Warden, John A. Col, USAF. *The Air Campaign*. Washington: Pergamon-Brassey's International Defense Publishers, 1989.

21. Youngren, Mark A., Lt Col, USA. "Possible Thesis Topics." Joint Staff, J-8/CFAD, Washington. Correspondence. June 1993.

22. ZOOM/XMP. Version 2.1, VMS System. Computer Software. Boyd and Fraser Publishing Co. Danvers MA, 1988.

VITA

Major Brian J. Griggs was born on 8 January 1958 in Ann Arbor, Michigan. Upon graduation from Centerville High School, Centerville, Ohio, in 1976 he entered the USAF Academy. Major Griggs graduated from the Academy and was commissioned as a Second Lieutenant in 1980.

After graduation from Undergraduate Pilot Training at Vance AFB, Oklahoma, Maj Griggs was assigned to Vance as a T-38 Instructor Pilot where he accrued nearly 1000 hours in the T-38. In 1984 he was assigned to the 366 TFW at Mountain Home AFB, Idaho, where he was an Instructor Pilot and Flight Examiner in the EF-111. In 1988 he was assigned to the 48 TFW at RAF Lakenheath in the United Kingdom. Here he was an F-111F Instructor Pilot, Flight Commander, and Assistant Chief of Wing Readiness.

Major Griggs entered the School of Engineering, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, in 1992 with a total of 2600 flying hours. After graduation, he was assigned to the Pentagon.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY (Leave blank)	2 REPORT DATE	3 REPORT TYPE AND DATES COVERED
	March 1994	Master's Thesis

4. TITLE AND SUBTITLE

AN AIR MISSION PLANNING ALGORITHM FOR A THEATER LEVEL COMBAT MODEL

5. FUNDING NUMBERS

6. AUTHOR(S)

Major Brian J. Griggs, USAF

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Institute of Technology, WPAFB OH 45433-6583

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/GST/ENS/94M-5

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

LtCol Mark Youngren
The Joint Staff, J-8/CFAD
Room 1D940, The Pentagon
Washington DC 20301-8000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This thesis describes the development of an air mission planning algorithm for the Joint Staff's Future Theater Level Model (FTLM). The overall problem scope was to develop an algorithm to handle major factors bearing on the combat mission planning problem while providing hook-ups for the FTLM architecture. Other aspects of the problem included finding the appropriate level of detail, developing a fast solving technique, and attempting to use existing data. The problem was handled by using some ideas from existing aircraft allocation algorithms and by adding some new techniques.

The proposed air mission planning algorithm supplies the optimum degree of force for campaign objectives by using a linear program (LP) to allocate the optimum number and type of aircraft and munitions against each target. The LP takes advantage of the force multiplying effects of mass and mutual support through its use of strike packages with SEAD and air-to-air escort. Additionally, a decision tree algorithm determines the best plan in light of the uncertainties of weather and weather forecasts.

This air mission planning algorithm omits many of the details in the actual aircraft tasking process, but provides fast, nearly optimal solutions which should approximate real world tasking results.

14. SUBJECT TERMS

aerial warfare, Air Force operations, linear programming, mathematical models

15. NUMBER OF PAGES

72

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and title page. Instructions for filling in each block of the form follow. It is important to ***stay within the lines*** to meet ***optical scanning requirements***

Block 1. Agency Use Only *(Leave blank)*

Block 2. Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

Block 3. Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

C -	Contract	PR -	Project
G -	Grant	TA -	Task
PE -	Program Element	WU -	Work Unit Accession No.

Block 6. Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. Performing Organization Name(s) and Address(es). Self-explanatory.

Block 8. Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. Sponsoring/Monitoring Agency Name(s) and Address(es). Self-explanatory.

Block 10. Sponsoring/Monitoring Agency Report Number. *(If known)*

Block 11. Supplementary Notes. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of...; To be published in.... When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. Distribution/Availability Statement. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR)

- **DOD** - See DoDD 5230.24, "Distribution Statements on Technical Documents."
- **DOE** - See authorities.
- **NASA** - See Handbook NHB 2200.2.
- **NTIS** - Leave blank.

Block 12b. Distribution Code.

- **DOD** - Leave blank.
- **DOE** - Enter DOE distribution categories from the Standard Distribution for Unclassified Scientific and Technical Reports.
- **NASA** - Leave blank.
- **NTIS** - Leave blank.

Block 13. Abstract. Include a brief *(Maximum 200 words)* factual summary of the most significant information contained in the report.

Block 14. Subject Terms. Keywords or phrases identifying major subjects in the report.

Block 15. Number of Pages. Enter the total number of pages.

Block 16. Price Code. Enter appropriate price code *(NTIS only)*

Blocks 17. - 19. Security Classifications. Self-explanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

Block 20. Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.